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Capacity design methods for strongback braced frames

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Capacity design methods for strongback braced frames

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Peter C. Talley
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Abstract

When subjected to strong earthquake ground motions, conventional steel braced frames are vulnerable to soft-story mechanisms, whereby the weakest story accumulates more damage relative to the rest of the structure. This reduces the overall strength of the structure, increases the cost of repairs, and can cause issues during the design process due to the reduced redundancy of the system.

One method for mitigating this behavior is the use of an elastic spine frame. These frames combine a stiff vertical "spine", such as a truss or shear wall, with a more ductile, energy-dissipating system. The spine typically spans the height of the structure and is designed to remain elastic, distributing earthquake demands across the height of the structure and bridging weak stories. One proposed elastic spine frame is the "strongback" braced frame, which merges a steel buckling-restrained braced frame and an elastic truss, using the buckling-restrained braces for energy dissipation and the truss for force distribution.

However, strongback braced frames do not have well-established design criteria. Specifically, there is no generally accepted method for ensuring that the strongback remains elastic, and seismic performance factors have not been developed. Additionally, conventional capacity design underestimates the demands on the spine. It is desirous to have a method for design of these frames that hews closely to existing methods utilizing the equivalent lateral force method.

This thesis presents the first phase of a study to address these gaps in the design provisions and to better understand the behavior of this system. A suite of building frames which employ the strongback system were designed with the intent of using them as the basis for parametric analytical studies in the second phase. The suite of frames was selected using the requirements of FEMA P695, the state-of-the-art method for determining seismic performance factors. Three alternative capacity design methods were developed and compared to basic capacity design to identify which is best suited to efficiently achieve the performance objectives. The methods were evaluated for efficiency in the design process, and for feasibility of the resulting designs. However, evaluation of performance objectives is the goal of future study.

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Chapter 1

Introduction and Literature Review

When subjected to strong earthquake ground motions, conventional steel braced frames are vulnerable to soft-story mechanisms, whereby the weakest story accumulates more damage relative to the rest of the structure. This reduces the overall strength of the structure, increases the cost of repairs, and can cause issues during the design process due to the reduced redundancy of the system (AISC 2018; Sabelli 2001).

Improving the behavior of braced frames—e.g. reducing damage concentration, reducing residual drifts, and increasing energy dissipation—has been done in numerous ways. These methods range from stricter requirements for connections and ductility-based member limitations to ideas for entirely new seisimc force resisting systems (SFRS) based on the braced frame geometry.

One class of SFRS that can be based on braced frame geometry is the elastic spine frames. These frames are dual systems that combine a stiff "spine", typically running the height of the building and designed to remain elastic during an earthquake, with a ductile, energy-dissipating component. The energy-dissipating component is intended to attract and absorb the earthquake demands, protecting the rest of the structure. The spine distributes seismic forces across the height of the building to the dissipators, bridging weak stories and preventing damage concentration. The dissipators are often, though not necessarily, made to be easily replaceable, as a sort of "fuse" that can be swapped out after a major earthquake (Eatherton et al. 2014; Burton et al. 2016; Chen et al. 2017).

An elastic spine frame based on braced frame geometry, termed the "strongback" braced frame, uses a stiff truss with conventional braces for the spine and buckling-restrained braces for the energy dissipating elements (Lai and Mahin 2014). However, design requirements for these frames are not well defined, and the design methods permitted for them under current building codes are complex and do not necessarily even account for the forces actually present in the structure (Panian et al. 2015; Simpson and Mahin 2018; Simpson 2018).

1.1 Seismic design

Seismic design in the United States has traditionally focused, to the exclusion of other criteria, on the safety of people inside structures during a seismic event—commonly called "life safety" (AISC 2018). Buildings are designed to accommodate significant permanent deformation of the main seismic-force-resisting system (SFRS), increasing the dissipation of earthquake energy and allowing those inside to escape the structure prior to collapse. Re-use after design-level earthquakes is not a design consideration for most structures.

Most seismic design for buildings in the United States follows one of the methodologies defined within *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, published by the American Society of Civil Engineers (ASCE) and commonly referred to as ASCE 7-16 (ASCE 2016). ASCE 7-16 also provides for the use of "performance-based design" (PBD), which allows the engineer to design structures according to project-specific requirements and avoid the prescriptive requirements of the standard. The engineer must demonstrate that the design achieves the same or better level of safety and reliability as a prescriptive design. PBD is required when designing a structure using a system that does not have accepted, established criteria.

1.1.1 Equivalent lateral force method

The most commonly used prescriptive seismic design methodology in ASCE 7-16 is the equivalent lateral force (ELF) method. The ELF method provides a means to capture the inelastic dynamic behavior of a structure through an elastic static analysis. It can be easily checked with hand calculations and does not require the selection of ground motions. Earthquake intensity is determined using site-specific accelerations and soil classification. Inelastic effects are accounted for using three "seismic performance factors" that are dependent on the specific SFRS being used: R, C_d, and Ω_0.

The response modification coefficient, R, reduces design loads. This reflects the "capping" of the force demand on the structure due to yielding of the SFRS. More ductile systems have higher R factors, leading to increased energy dissipation and reduced loads, at the cost of greater deflection. This is captured by the deflection amplification factor, C_d, which directly multiplies the deflections calculated from the elastic analysis. For some highly ductile or highly flexible systems such as moment frames, member size is often controlled not by strength demands, but instead stiffness requirements or stability limits.

The overstrength factor, Ω_0, captures the inherent overstrength of the system; that is, additional strength that is not accounted for during the design process. Sources of overstrength include safety factors used in design and lower-bound assumptions of material strength. Many SFRS have elements that must remain essentially elastic to ensure structural integrity or because they cannot be guaranteed to provide reliable inelastic behavior. The strength of these elements must therefore be checked against the "expected" strength of the system. The overstrength factor provides one method of doing this indirectly by scaling the applied design seismic loads (ASCE 2016).

Use of the overstrength factor, however, provides neither an upper nor a lower bound on system overstrength, only an estimation of the potential behavior. An alternative to the use of overstrength which can provide an upper bound is capacity design. Instead of amplifying the design loads directly, the system is placed into the fully yielded state directly, with the expected loads from the yielded members applied to the rest of the frame. These expected loads are calculated directly from expected variance in material strength, instead of attempting to capture all the variation in a single factor for all instances of an SFRS (AISC 2016a).

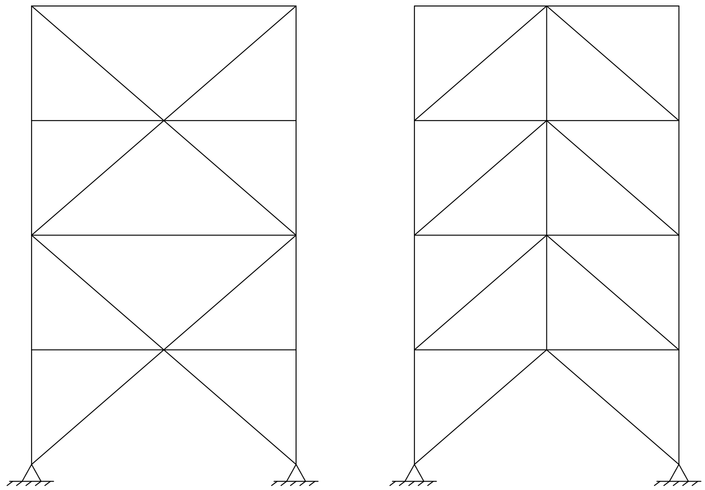

Figure 1.1: X-bracing (left) and zipper-braced frame (right).

1.2 Steel braced frames

Steel braced frames are widely used as a lateral force resisting system due to their increased stiffness, relative economy, and ease of construction compared to moment frames (AISC 2018). Despite this, they have a vulnerability to soft-story mechanisms, whereby the weakest story accumulates more damage—usually measured in terms of permanent story drift—relative to the rest of the structure. These mechanisms reduce the overall strength of the structure, increase the cost of repairs after major seismic events, and can cause issues during the design process due to the reduced redundancy of the system (Sabelli et al. 2003).

Various methods exist for mitigating these issues with braced frames. Additional detailing requirements, such as those for special concentrically-braced frames (SCBF) have greatly improved braced frame ductility. Transfer of load between stories can be significantly affected by adjustments to brace layout, such as the use of multi-story X-bracing or zipper-braced frames, shown in Fig. 1.1. Multi-story X-bracing, which alternates the direction of the braces at each story, provides greater continuity between floors than chevron bracing. Zipper-braced frames provide transfer of load between stories using tie braces running up the center of the frame, linking the work points of each story's diagonal braces (Khatib et al. 1988).

1.2.1 Buckling-restrained braces

The development of buckling-restrained braces (BRB) also addresses issues of ductility and load transfer. These braces are specially designed members that restrict the buckling behavior of the brace. The most common design is a steel plate core encased in a grouted steel tube—see Fig. 1.2. The tube and grout increase the buckling load of the steel core, but do not themselves carry axial load. This allows the core to fully yield in both tension and compression, removing the "pinch" in the hysteretic behavior of typical braces—compare Figs. 1.3 and 1.4—and greatly increases the energy dissipated by the system. Buckling-restrained braces demonstrate little to no strength degradation as they cycle, instead hardening and yielding multiple times

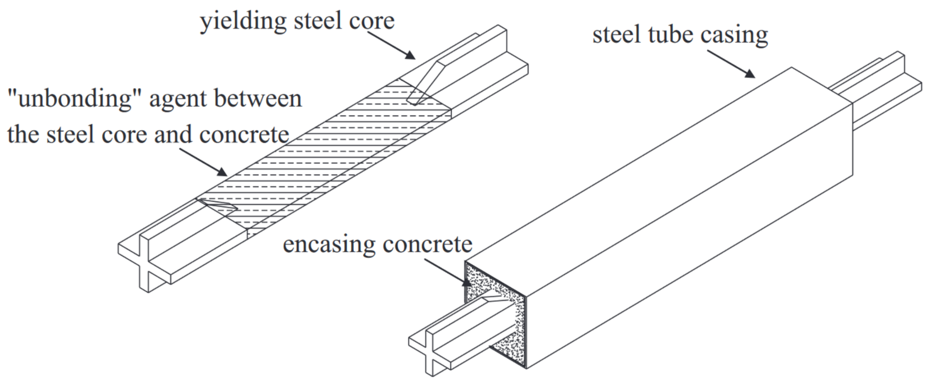

Figure 1.2: Buckling-restrained brace components.
Reproduced from Talebi et al. (2014).

until fracture (Black et al. 2004).

Buckling-restrained braces on the whole remain proprietary systems, the design of which is handled by the manufacturer of the brace. Often, the manufacturer will design the connection of the brace to the surrounding frame as well, with the design engineer providing only the type of connection and either the required axial strength or the required cross-sectional area of the core (AISC 2018).

1.2.2 Dual systems and spine frames

Another recognized method of improving braced frame behavior is use of a dual system: the combination of a braced frame and another SFRS with a different response profile. The addition of a moment frame system, for example, improves the vertical continuity of the SFRS and can compensate for weaknesses that may develop in the stronger, stiffer braced frame. The combination thus reduces damage concentration and residual drifts compared to either system in isolation (Giugliano et al. 2010).

Overlapping with dual systems are the spine frames. Also termed mast frames or masted systems, these systems usually combine a stiff elastic "spine" with a more ductile frame. The spine stiffens the structure and distributes demand across stories, and the ductile frame provides the necessary energy dissipation. The concept is not limited to any particular material or geometry. The spine may be a concrete shear wall or a steel truss; it may be central to the system or it may be offset; the ductile frame may consist of buckling-restrained braces or a moment frame or any other sufficiently ductile system.

Elastic spine frames are distinguished in their design and behavior by an explicit goal to prevent permanent damage to the structure. Instead of having to demolish or extensively retrofit a building after a seismic event, a building utilizing these systems would, ideally, only require replacement of the ductile elements that provide energy dissipation. Thus, while potentially broad in concept, most examples of elastic spine frames have focused on providing explicit "seismic fuses", with forces distributed to those fuses by the elastic spine.

These fuses vary in concept; the self-centering rocking braced frame proposed by Eatherton et al. (2014)

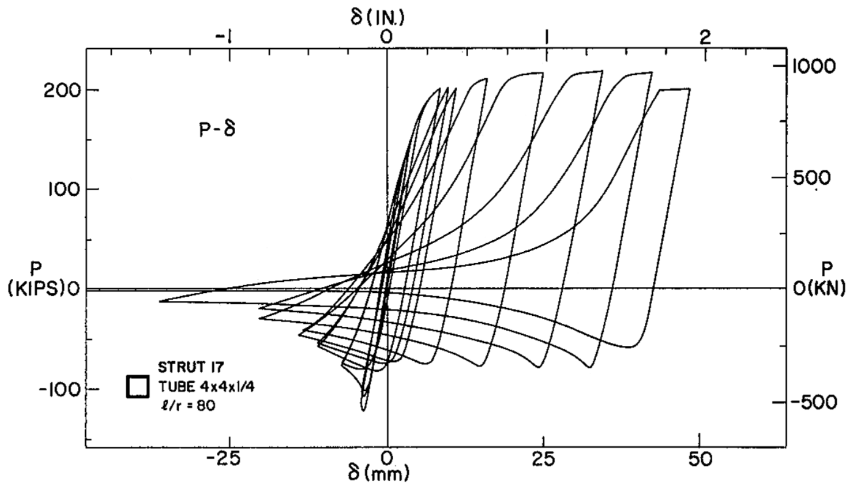

Figure 1.3: Hysteretic response of conventional brace.
Reproduced from Popov and Black (1981).

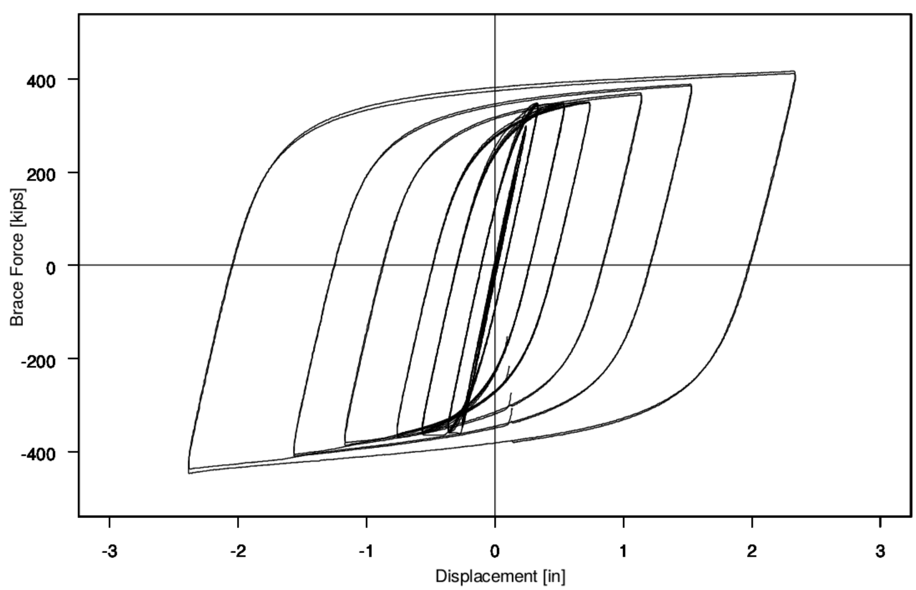

Figure 1.4: Hysteretic response of buckling-restrained brace.
Reproduced from Clark et al. (2000).

combines a stiff braced frame with "shear fuses" that provide energy dissipation and post-tensioned cables that provide a restoring force to reduce or eliminate residual drifts. Design of the rocking frame requires consideration of higher mode effects, however. Burton et al. (2016) examined a conceptually similar system for concrete moment frames, where the spine is provided by masonry infills. Chen et al. (2017) considered a hybrid spine system where an elastic braced frame provides the spine, energy dissipation is provided by buckling-restrained columns at the base of the spine, and the restoring force is provided by elastic moment frames flanking the spine.

1.3 Strongback braced frame

The strongback braced frame (SBF) examined in this thesis is a particular kind of spine frame. A steel truss, pinned at the base, composes the spine (the eponymous "strongback") and BRBs form the ductile system. It was originally proposed by Lai and Mahin (2014), who extended it from the concept of zipper-braced frames (Khatib et al. 1988), tied eccentrically-braced frames, and elastic truss systems (Tremblay 2003). The truss geometry of the strongback is particularly suited to the retrofitting of older braced frames (Simpson and Mahin 2017).

SBFs distribute forces across the height of the structure through the elastic strongback, resisting the formation of soft stories and reducing residual drifts. If made sufficiently stiff, it is possible to efficiently use—i.e., fully use the available capacity—BRBs of identical size and configuration at each story, instead of the usual decrease in size with height. Such usage is potentially desirable, as common components simplify construction and can reduce costs. This thesis, however, is primarily concerned with the strength limit states of the strongback, and so uniform BRBs are not considered.

1.3.1 Previous studies

Lai and Mahin (2014) examined the potential of the strongback to mitigate soft story behavior, using numerical analyses to compare concentrically-braced frames without strongbacks to those with strongbacks. Several frames were designed using the provisions of ASCE 7-05, with design of the strongback itself performed using overstrength load combinations for the primary braces and capacity-limited loads for the tie braces. Nonlinear pushover and dynamic analyses were performed to verify the design. They found that this design methodology was sufficient to significantly improve the distribution of forces along the height of the structure, and that the strongback could, potentially, be a more economical system than a conventional SCBF.

Panian et al. (2015) present a case study of the design and construction of a four-story building utilizing SBF, with a particular eye towards the redundancy provided by the strongback itself. The objective of this focus was to avoid triggering the redundancy provisions of ASCE 7 that require a 30% increase in the applied seisimc load. Design was accomplished using response spectrum analysis (RSA) and overstrength load combinations, using the same size of BRB at each level. Their analysis showed that the redundancy requirements were satisfied by the strongback, and reduced the total number and area of BRBs required for the structure.

Simpson and Mahin (2017) considered the design and experimental evaluation of a retrofit SBF. The original frame was a two-story concentrically-braced frame in a chevron configuration, highly vulnerable to soft-story

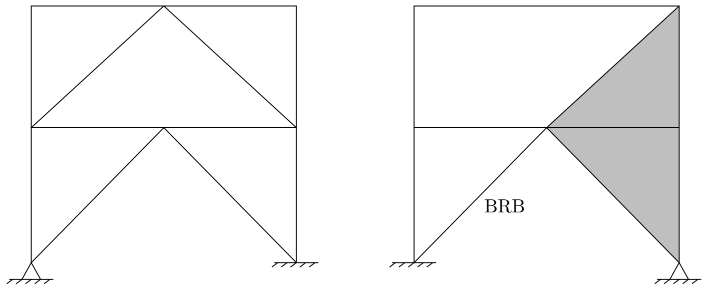

Figure 1.5: Retrofit of CBF (left) to SBF (right).
Adapted from Simpson and Mahin (2017)

behavior. The retrofit left the columns and beams as-is, replacing one side of the bracing with a single BRB on the first floor, and replacing the other side with an x-braced strongback (see Fig. 1.5). The new BRB was sized using an assumed lateral load distribution, with the base shear being the maximum base shear the testing setup could provide. The new braces and connections of the strongback were designed to withstand the capacity effects from the BRB and beams, amplified by a factor of 1.1.

Simpson and Mahin (2018) focused on determining the relative stiffness required to enforce the desired story drifts. The same BRB size was used at each story. The first story strongback brace was found to control the elastic response of the strongback, with braces at higher levels seeing lower loads. By varying the size of the strongback braces—using cross-sectional area—they determined that a first story brace with approximately six times the area of the corresponding BRB was necessary to achieve the desired drifts. Braces at higher levels were assigned an area 60% of the first story brace.

Palermo et al. (2018) examined the response and distribution of forces in spine frames where the spine is not integrated into the primary frame. In this study the strongback was idealized as a rigid column pinned at the base, and the behavior of the strongback paired with frames dominated by shear deformations (termed “shear type”, or ST) was compared to the behavior when paired with frames dominated by flexural deformations (termed “pendulum type”, or PT). The ST frames were represented by moment frames with infinitely rigid beams, while the PT frames were represented by moment frames with pinned connections to the columns. Both ST and PT frames were assumed to have linear elastic behavior. For both uniform and inverted-triangular lateral force distributions, the ST frames were found to have uniformly distributed story shears, while the PT frames concentrated shear in the first story and generated higher moments in the strongback. As braced frames, SBFs are expected to hew more closely to ST behavior.

1.3.2 Design methods

No consensus method for design of SBFs by the ELF method exists. Seismic performance factors have not been established. Previous studies have used the factors for steel BRBF when using BRBs and SCBF when using conventional braces. Design of the energy-dissipating braces is straightforward; the elastic nature of the rest of the system allows them to be designed using standard static methods (Simpson and Mahin 2018). The immediate design concern then is how to ensure the strongback remains elastic.

The conventional method of capacity design for concentrically-braced frames carries the assumption that the load effect is predominantly in the first mode, excluding the effects from higher modes. However, because the strongback remains elastic, it continues to attract demand past the point that the inelastic system has yielded. Higher mode effects become prominent in the system as the strongback pivots and flexes, and must be accounted for (Simpson 2018).

1.4 FEMA P695 methodology

Quantification of Building Seismic Performance Factors, commonly referred to as FEMA P695 (FEMA 2009), is the state-of-the-art methodology for determining appropriate values for the seismic performance factors. FEMA P695 outlines a standardized procedure for developing a suite of buildings, called archetypes, that are used to perform nonlinear static and dynamic analyses. These analyses are used to iteratively arrive at the appropriate performance factors by ensuring a uniform chance of failure.

The archetypes are intended to represent the range of potential structures that have already been or will be constructed using the SFRS in question. All the particular details do not need to be covered, but full coverage of the design space for a system may still require a significant number of archetypes. Variations in gravity load level, structural period (mostly a function of the height), and layout are all required to be adequately covered. However, the methodology allows for the removal from consideration of archetypes that do not control the evaluation of the design space. The determination of this is largely left to the judgment of the user, but is difficult to know a priori, and is primarily done iteratively throughout the development and analysis of the archetypes.

The methodology strongly suggests that archetypes be designed according to the equivalent lateral force method, except when ELF is not permitted for the particular situation. For example, ELF is not permitted for design of structures in seismic design category D greater than 48.8 m (160 ft) tall (ASCE 2016). In these situations, the recommended alternative is response spectrum analysis (RSA), which obtains the design lateral forces by enveloping the modal response of multiple modes, not just the first mode. RSA is permitted, but not required, when it is known or expected that RSA will be a more common design method in practice than ELF.

Once designed, archetypes are subjected to nonlinear pushover and response history analyses to determine behavior prior to collapse and when collapse occurs, respectively. Pushover analyses provide ductility and overstrength measures, while the response history analyses are compiled through a method called incremental dynamic analysis to determine the probability of collapse. A standard suite of 44 “far-field” ground motions—22 events, with 2 directional sets each—is preselected by the methodology. An additional set of ground motions is provided by the methodology for analysis of buildings designed for near-fault conditions.

Since its publication in 2009, there have been multiple updates to the standards FEMA P695 stipulates be used. This work uses those updated versions, including the 2016 edition of *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. Additionally, the methodology defines C_d as equal to R, but C_d continues to almost always be specified as less than R in ASCE 7-16 (ASCE 2016). As the archetypes are intended to represent the range of actual potential designs, this work follows ASCE 7-16 in using separate C_d values.

Table 1.1: Relevant FEMA P695 studies

Citation	Frame Type	Number of Archetypes
Blebo and Roke (2018)	Self-centering controlled rocking braced frame	9
Bozkurt and Topkaya (2016)	Buckling-restrained braced frame (BRBF)	3
Denavit (2012)	Composite special concentrically-braced frame	24
Denavit et al. (2016)	Composite special moment frame	36
Hsiao et al. (2013)	Special concentrically-braced frame	12
NIST (2010)	Buckling-restrained braced frame	10
NIST (2010)	Buckling-restrained braced frame—Full design space	128
NIST (2010)	Special concentrically-braced frame	10
NIST (2010)	Special moment frame (SMF)	20
Kuşyılmaz and Topkaya (2016)	Eccentrically-braced frame	6
Miyamoto et al. (2011)	Special moment frame with viscous damper	10
Rahgozar et al. (2016)	Self-centering controlled rocking braced frame	12
Verma and Sahoo (2018)	Steel plate shear wall	6
Zareian et al. (2010)	Special moment frame	20
Zaruma and Fahnestock (2018)	Buckling-restrained braced frame and BRBF/SMF	19
Zsarnóczay and Vigh (2017)	Buckling-restrained braced frame	24

1.4.1 Example studies

NIST (2010) evaluated the use of the FEMA P695 methodology for seven seismic force resisting systems, including a trial application determining the full design space of BRBF. They determined that full coverage of BRBF would require 128 archetypes across 32 performance groups, but reduced that number to 15 unique archetype configurations across 6 performance groups. This was done through the use of sensitivity studies, varying individual parameters to determine their effect on the design of a subset of the selected design space. Analytical models were not developed to verify the selection, and the final set of 15 archetypes could be found to not actually be the critical set.

When evaluating BRBF for the Eurocode, Zsarnóczay and Vigh (2017) considered 24 archetypes across 8 performance groups, but only one specific brace configuration. Archetypes varied from 2 to 8 stories, and also varied seismic and gravity loads. Zaruma and Fahnestock (2018) considered 13 BRBF archetypes as well as 6 dual BRBF/special moment frame archetypes, ranging from 4 to 15 stories. All archetypes were designed using RSA except for one BRBF that was designed using ELF.

When evaluating self-centering rocking frames, Rahgozar et al. (2016) considered 12 archetypes across 4 performance groups. Only one frame configuration was considered, as the test data required by the methodology was only available for that configuration. Blebo and Roke (2018) considered a different configuration of the self-centering rocking frame, with buckling-restrained columns for energy dissipation instead of fuses. 9 archetypes were considered.

A listing of relevant FEMA P695 studies consulted for this work is presented in Table 1.1. Several trends make themselves apparent: first, many studies analyze a relatively small number of archetypes, sometimes as few as three. FEMA P695 suggests that twenty to thirty archetypes are most likely needed, but within the relevant studies, the median is only twelve archetypes.

1.5 Objectives

The strongback braced frame system has not previously been analyzed using the FEMA P695 methodology. This thesis seeks to develop a comprehensive set of strongback frames suitable for analysis by the methodology and to study the effect of designing strongback frames according to various modifications to basic capacity design. A much broader set of archetypes than is usually found in the literature is desired, so as to help determine the efficacy of paring down the design space.

Design using overstrength load combinations has several pitfalls already discussed, and basic capacity design may be inappropriate for design of strongbacks due to the assumed mode. It is an additional goal of this work is to determine whether modifications to basic capacity design can overcome this issue. The modifications considered are (1) amplification of first-mode capacity effects, (2) inclusion of capacity effects due to higher modes, and (3) application of all possible permutations of the capacity effect pattern.

In total, 56 archetypes are considered, each designed according to the four different capacity methods. For the 13 2-story structures, the modal and permutation cases result in the same loading, bringing the total number of unique designs to 211.

Chapter 2 describes the selection of archetypes and defines the design space considered. Chapter 3 covers the design procedure, including selection of loads and design standards. Chapter 4 presents a few sample designs and important observations. Chapter 5 provides conclusions, recommendations, and avenues for further study. A full listing of designed archetypes is provided in the Appendix, along with detailed design information.

Chapter 2

Selection of Archetypes

The methodology described in *Quantification of Building Seismic Performance Factors*, commonly referred to as FEMA P695, requires the selection and design of a suite of archetype buildings that "capture the essence and variability of the performance characteristics of the system of interest" (FEMA 2009). Each archetype is intended to represent a possible configuration of the expected use of the examined system in practice. The methodology recognizes that representing every possible permutation is infeasible, and instead stipulates the careful selection of parameters.

In developing the archetype suite, FEMA P695 considers a few parameters especially important. Expected variations in building configuration are the primary focus, followed by the effects of fundamental period and different gravity load levels.

2.1 Configurations

The strongback braced frames (SBF) in this study use A992 wide-flange (W) beams and columns, and square A500 Grade C hollow structural sections (HSS) for the lateral and tie braces in the strongback. Buckling-restrained braces, with a minimum yield strength of 260 MPa (38 ksi) are used for the energy-dissipating elements. The bases of the columns are assumed to be pinned connections, and the beams are assumed to be laterally braced at the midpoints between columns and tie braces. If a tie brace does not frame into the beam at a particular story, the beam is assumed to have only one point of bracing at midspan.

The exact configuration of an SBF is not standardized, and three brace configurations are considered in this study: multi-story X-bracing (X), chevron bracing (C), and multi-story X-bracing with offset centerline (Xo). These configurations are based on those in Lai and Mahin (2014), and are illustrated in Fig. 2.1. X-bracing and chevron bracing are simple adaptations of existing concentrically-braced frame designs, with the only change being that half the frame is now a strongback truss held together with tie braces. Offset X-bracing shifts the position of the ties and intersection of the braces with the beams, with the intent of reducing strain in the buckling-restrained braces (due to a different angle) and potentially reducing the required size of the strongback.

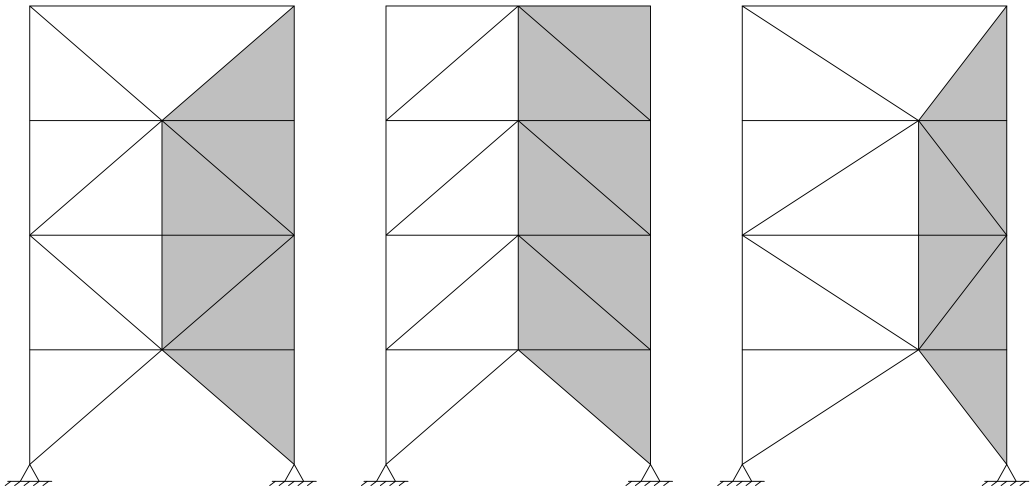

Figure 2.1: Primary strongback configurations.
Left-to-right: X, C, Xo. Strongback side of the frame marked by shading.

Other SBF configurations have been proposed that are not considered in this study. Two are shown in Fig. 2.2. The most studied is a configuration that places the spine outside of the main seismic force resisting system instead of having it integrated. This configuration was studied in idealized form by Palermo et al. (2018), who focused on comparing the effects of the strongback on flexural-deformation-dominated systems versus shear-deformation-dominated systems. Lai and Mahin (2014) also proposed the use of the strongback spine with a single, large, energy-dissipating device at the ground floor. This configuration was termed the single energy dissipator (SED) configuration, and would rely almost entirely on the strongback's ability to remain elastic and carry forces to the dissipator.

2.2 Fundamental period

To help ensure that different studies produce comparable results, FEMA P695 defines the fundamental period T to use for archetypes as Eq. (2.1). The methodology strongly recommends that archetypes from both the short-period (constant acceleration) and transition-period (constant velocity) domains be considered, while excluding archetypes from the long-period domain ($T \geq 4.0\,\mathrm{s}$) outright. Short- and transition-period domains are separated by the transition period T_s, defined by Eq. (2.2).

$$T = C_u T_a = C_u C_t h_n^x \geq 0.25\,\mathrm{s} \tag{2.1}$$

Where:

C_u	=	Coefficient based on local seismicity (ASCE 7-16 Table 12.8-1)
T_a	=	Approximate fundamental period, s
C_t, x	=	Parameters for approximate fundamental period (ASCE 7-16 table 12.8-2)
h_n	=	Height of the structure, m (ft)

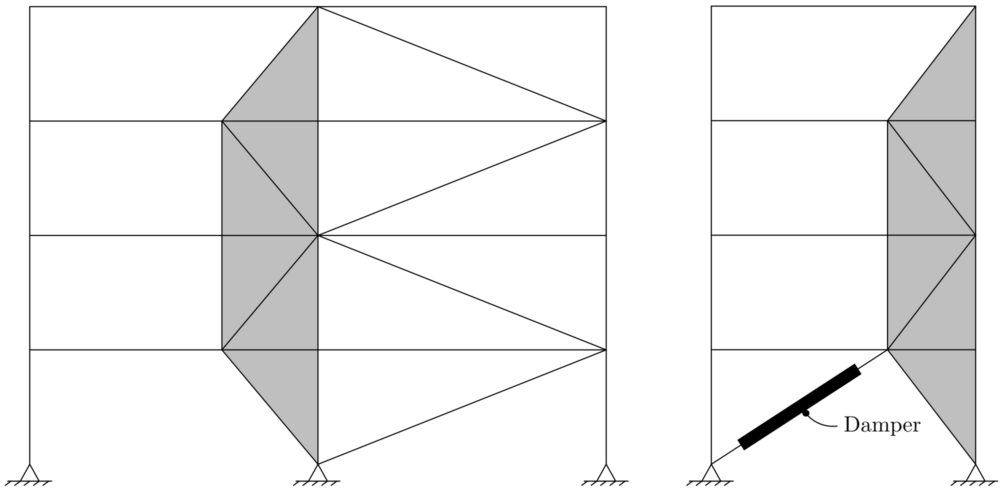

Figure 2.2: Other proposed strongback configurations.
Left: Strongback external to braced frame. Right: Single energy dissipator setup.

$$T_s = \frac{S_{D1}}{S_{DS}} \tag{2.2}$$

Where:

S_{D1}	=	Design spectral response acceleration parameter at a period of 1.0 s (g)
S_{DS}	=	Design spectral response acceleration parameter in the short-period domain (g)

S_{D1} and S_{DS} are site-specific, and the methodology provides standardized values based on the seismic design category being considered.

The tabulated parameters C_t and x are dependent on the SFRS used, and are tabulated in ASCE 7-16 table 12.8-2 (ASCE 2016). These parameters provide a conservative—i.e., resulting in greater loads—lower-bound approximation of the fundamental period based on the height of the structure. There is some uncertainty in which parameters to use: previous studies on strongback braced frames have largely assumed similar behavior to buckling-restrained braced frames when selecting design factors, but SBFs are intended to be significantly stiffer than BRBFs. This would indicate a lower fundamental period and higher base shear.

To resolve this, preliminary eigenvalue analyses were performed on BRBF and SBF frames. These analyses indicated that, in general, SBFs are stiffer than a corresponding BRBF of similar height and configuration, and the values for “All other structural systems” are more appropriate for SBFs than the values specifically for BRBFs. A comparison of the eigenvalue and estimated fundamental periods for the finished archetypes may be found in Fig. 4.1 and Table A.4.

The practical outcome of Eqs. (2.1) and (2.2) is that structural period in the methodology is primarily determined by the height of the structure, and that structures move into the transition-period domain beginning at 2 or 3 stories in height (for story heights of 10–20 ft, as considered in this study). This potentially

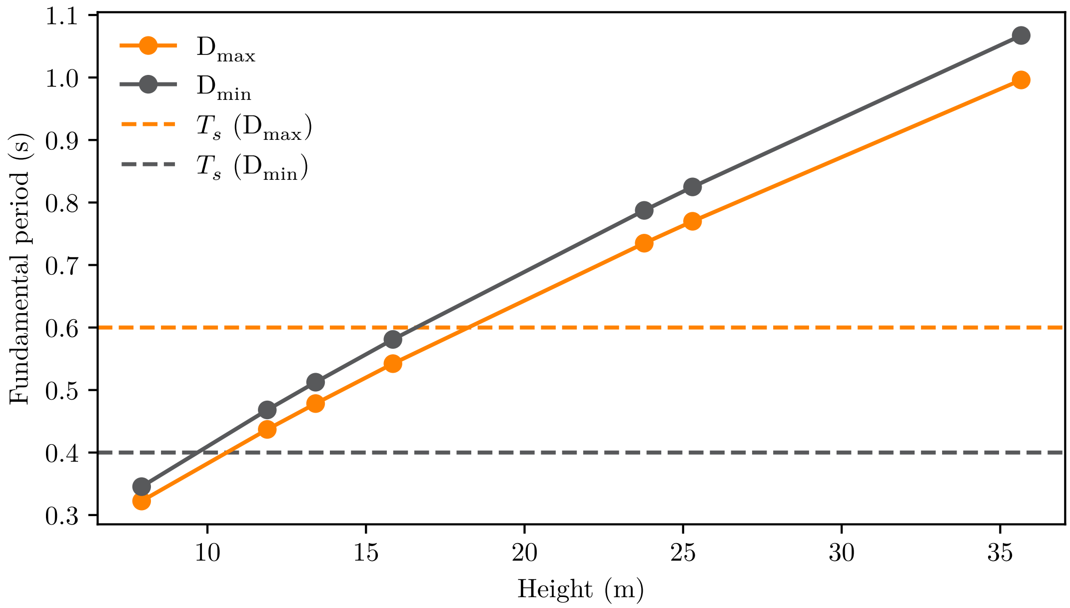

Figure 2.3: Fundamental period of archetypes.
See Eqs. (2.1) and (2.2) for formulation.

results in a dearth of short-period performance groups, and the methodology recommends considering additional configurations of short-period structures to flesh out the groups. For those systems, such as moment frames, where even very short structures may be flexible enough to be in the transition-period domain, it is permitted to reduce the number or size of short-period performance groups.

This final case occurs with strongbacks, as the purpose of the strongback—to distribute drift across multiple stories—precludes the inclusion of single-story archetypes. As such, the preliminary performance groups listed in Table 2.1 are weighted strongly towards transition-period archetypes. The fundamental period of each height variant in this study is shown in Fig. 2.3, plotted against the corresponding transition periods for a given seismic intensity level.

2.3 Archetype design space

Seismic design category D was used for all archetypes. This was selected because of the expected use of strongback systems in regions with high seismic loads. It is the highest seismic design category commonly considered under the FEMA P695 methodology; stricter categories are assigned by ASCE 7-16 based on local soil properties or nearness to a fault zone. As the standard set of ground motions provided by the methodology only covers earthquakes that occur in the "far-field" zone, i.e. not near a fault, these additional categories are not considered.

FEMA P695 prescribes upper- and lower-bound site-specific factors for each seismic design category, which are used to establish the seismic load magnitude. Archetypes using the higher factors (D$_{max}$) are expected to

Table 2.1: Preliminary performance groups

Performance Group	**Configuration**	**Bay Size**	**Seismic Intensity**	**Period Domain**	**Number of Archetypes**
1	X	9.14 m (30 ft)	D_{max}	Short	3
2				Long	2
3			D_{min}	Short	1
4				Long	3
5		6.10 m (20 ft)	D_{max}	Short	3
6				Long	1
7			D_{min}	Short	1
8				Long	3
9	Xo	9.14 m (30 ft)	D_{max}	Short	6
10				Long	3
11			D_{min}	Short	1
12				Long	3
13		6.10 m (20 ft)	D_{max}	Short	4
14				Long	2
15			D_{min}	Short	1
16				Long	3
17	C	9.14 m (30 ft)	D_{max}	Short	1
18				Long	3
19			D_{min}	Short	1
20				Long	3
21		6.10 m (20 ft)	D_{max}	Short	3
22				Long	1
23			D_{min}	Short	1
24				Long	3
$\sum$					56

Table 2.2: Archetype parameters

Parameter	Values	N
Number of stories	2, 3, 4, 6	4
Brace configuration	X, C, Xo	3
Bay size	6.10 m, 9.14 m (20 ft, 30 ft)	2
Seismic load intensity	D_{max}, D_{min}	2
Base number of archetypes		48
Special archetype variants	See Table 2.3	8
Total number of archetypes		56

control over those using the lower intensity (D_{min}), but this is not guaranteed. If D_{min} does control over D_{max}, the archetypes will need to be re-designed and re-analyzed for seismic design category C. C_{max} and D_{min} have the same intensities, but structures in seismic design category D have stricter requirements in general than those in seismic design category C.

The parameters selected for use in this study are based on previous studies of buckling-restrained braced frames and strongback braced frame systems (Fahnestock et al. 2007; NIST 2010; Lai and Mahin 2014; Panian et al. 2015; Simpson and Mahin 2017). Not all these previous studies have used the FEMA P695 methodology, but they have been included to better represent the expected SBF design space. Parameters that vary between archetypes are summarized in Table 2.2, and each archetype was given a unique identifier based on the variation of the parameters in Table 2.2. The identifier is constructed by:

```
<number of stories><configuration>-<bay width (ft)>-<seismic design category>[-<special>]
```

For example, archetype 2Xo-30-Dmax-Heavy has two (2) stories, has bracing in the Xo configuration (see Fig. 2.1), has 30 ft bays, is designed for seismic design category D_{max}, and uses the special higher gravity load setup.

2.3.1 Floor plan and gravity loads

A regular square floor plan, shown in Fig. 2.4, was used for all archetypes. Gravity loads for standard archetypes are based on an office-style building. Two bay sizes were considered: 6.10 m (20 ft) and 9.14 m (30 ft). These bay sizes are used to implicitly consider higher gravity loads at all building height variations. Explicitly higher gravity loads ("warehouse" loading) are also considered, but for a limited number of shorter archetypes.

2.3.2 Number and height of stories

As the purpose of the strongback itself is to distribute damage over multiple stories of a structure, no single-story archetypes were included in the suite. This tends to limit the number of structures in short-period performance groups, especially for design category D_{min}. This is accepted by the methodology as there are other systems, such as highly-ductile moment frames, that are similarly excluded from the short-period

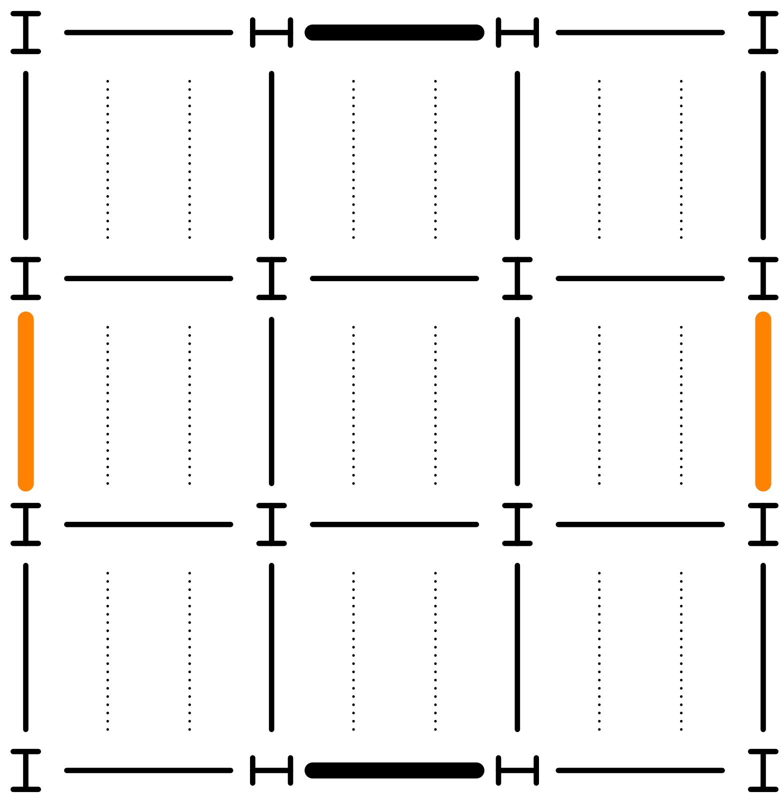

Figure 2.4: Building floor plan.
Seismic force resisting systems shown by bold lines, with frames designed for this study highlighted. Gravity frames shown by normal lines, with joists shown by dotted lines.

Table 2.3: Archetypes for focused studies

Variation	Archetype Names
Tall first story	3Xo-20-Dmax-Tall 3Xo-30-Dmax-Tall 6Xo-20-Dmax-Tall 6Xo-30-Dmax-Tall
Very high gravity load	2Xo-30-Dmax-Heavy 4Xo-30-Dmax-Heavy
Very tall archetypes	9Xo-30-Dmax 9X-30-Dmax

domain by their behavior and expected configurations.

The design space of strongback frames is, however, also limited to relatively short structures. Taller structures are subject to increased effects from higher modes and, potentially, prohibitively large member sizes. The story height of 3.96 m (13 ft) is typical of commercial construction. 2, 3, 4, and 6 story structures are considered. Two archetypes with taller first stories at 5.49 m (18 ft) were also developed, as well as two 9-story archetypes. From these heights, the fundamental periods of the archetypes were calculated, and are shown with the corresponding transition periods in Fig. 2.3.

2.3.3 Additional variants

Additional variants on these parameters were included for more focused study. These archetypes extend the design space, while keeping the number of designed archetypes to a manageable level, and are listed in Table 2.3.

Two 9-story archetypes were developed to examine the impact on taller structures. These structures experience increased effects from higher modes, which exacerbates the existing issue with strongback spines and forces from higher modes (Simpson 2018).

Four archetypes with 5.49 m (18 ft) first-stories were developed. A tall first story (relative to the other stories) is a common occurrence, and introduces a potential soft-story mechanism. These archetypes will help evaluate the ability of SBFs—and the design methods' ability—to bridge weak stories and mitigate damage concentration.

Two archetypes with explicitly higher gravity loads, beyond those added by the variation in bay width, are considered to investigate increased P-Delta effects. These archetypes provide insight into the effects of very high gravity loads, such as might be encountered in a warehouse or factory.

Chapter 3

Design of Archetypes

Design of the archetypes was performed according to *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, referred to as ASCE 7-16 (ASCE 2016), the *Specification for Structural Steel Buildings*, referred to as AISC 360-16 (AISC 2016b), the *Seismic Provisions for Structural Steel Buildings*, referred to as AISC 341-16 (AISC 2016a), the *2018 International Building Code*, referred to as the 2018 IBC (ICC 2017), and *Quantification of Building Seismic Performance Factors*, referred to as FEMA P695 (FEMA 2009), with some modifications. The design standards and relevant sections are summarized in Table 3.1.

This study uses the FEMA P695 methodology combined with updated design provisions to bring it up to date and in line with contemporary design practice. FEMA P695 specifies the use of ASCE 7-05, which has been revised twice since the publication of the methodology. The most recent edition, ASCE 7-16, is used along with the corresponding material specifications. Additionally, the deflection amplification factor C_d is not taken equal to the response modification coefficient R.

The physical justification for specifying $C_d = R$ in FEMA P695 is well-founded; research indicates that, for typical damping levels, the "Newmark rule" holds and inelastic and elastic deflections are approximately the same for systems with fundamental periods greater than T_s, and inelastic deformations are generally greater than elastic deformations for systems with periods less than T_s (FEMA 2009). However, it is not clear that it is necessary to do so; systems designed with the current tabulated values of C_d and R, where C_d is almost always less than R, perform adequately (Denavit 2012; ASCE 2016). If in the future changes are made to the design provisions such that $C_d = R$, it is expected that deflection limits would be correspondingly relaxed. As such, this thesis follows ASCE 7-16 in using tabulated values of C_d less than R, reflecting common design practice (NIST 2010).

The objective of this design process was not to develop complete, construction-ready building layouts. Rather, the intention was to produce archetypes that could be readily analyzed. To that end, connection detailing and design of the gravity system were omitted. FEMA P695 does not allow inclusion of the potential contributions of the gravity system to the strongback's lateral strength, but the destabilizing effect due to second-order effects was included through the use of a leaning column in the model. (Flores et al. 2012).

Table 3.1: Design standards for archetypes

Design Criteria	Reference	System	Columns	Beams	BRBs	Strongback
Member strength	AISC 360-16		Ch. H	Ch. F	[1]	Ch. E
Seismic drift limit	ASCE 7-16	§12.12.1				
Stability coefficient	ASCE 7-16	§12.8.7				
Expected strength	AISC 341-16		Table A3.1	Table A3.1	§F4.2a	Table A3.1
Brace capacity strength	AISC 341-16		§F4.3	§F4.3		§F4.3
Mod. ductile section	AISC 341-16		§D1.1			§D1.1
Highly ductile section	AISC 341-16			§D1.1		
Deflection limits	2018 IBC			Table 1604.3		

[1] Buckling-restrained braces were designed according to the recommendations in the 3$^{\text{rd}}$ edition *Seismic Design Manual* (AISC 2018).

3.1 Model

Analyses for the design process were performed using two-dimensional, elastic, primarily geometrically-nonlinear models. Members were modeled in SAP2000 with idealized connections and stiffness based on gross section properties (Computers and Structures, Inc. 2017). Beams and braces used pinned connections, while the frame columns were modeled as continuous with pinned bases. Beams, columns, and conventional braces used centerline beam-column elements with shear deformations included. Only one half of an archetype structure was modeled at a time, with the tributary gravity columns and perpendicular frame columns represented by a single column free to rotate at each story.

An four-story example using the X-bracing setup is shown in Figs. 3.1 and 3.2. Fig. 3.1 shows the setup of the frame, with the leaning column (representing the tributary gravity system) detached from the seismic force resisting system. Fig. 3.2 shows the idealized connections used throughout the model.

Buckling-restrained braces (BRBs) require special consideration when modeling to capture their behavior. This was accomplished using truss elements and a stiffness modification factor of 1.5 (NIST 2015). This stiffness factor is applied to the cross-sectional area of the BRB core, and is used only in the analysis to determine force distribution. Strength checks on the BRBs are performed using the unfactored area of the core.

3.2 Loads

Loads on the structures were developed according to ASCE 7-16 and AISC 341-16. ASCE 7-16 provided dead, live, and seismic loads, and AISC 341-16 provided the capacity-limited seismic load. Wind, rain, and snow loads are not included. Wind load is not required for the development of archetypes. Snow and rain loads vary independently of seismic loads, and do not significantly impact seismic performance (FEMA 2009).

Where relevant, the importance category was assumed to be II, and any importance factor set to 1.0. The redundancy factor from section 12.3.4 of ASCE 7-16 is also assumed to be 1.0. Inclusion of the redundancy factor in archetype designs is potentially unconservative for collapse evaluation, as the increased loads in the

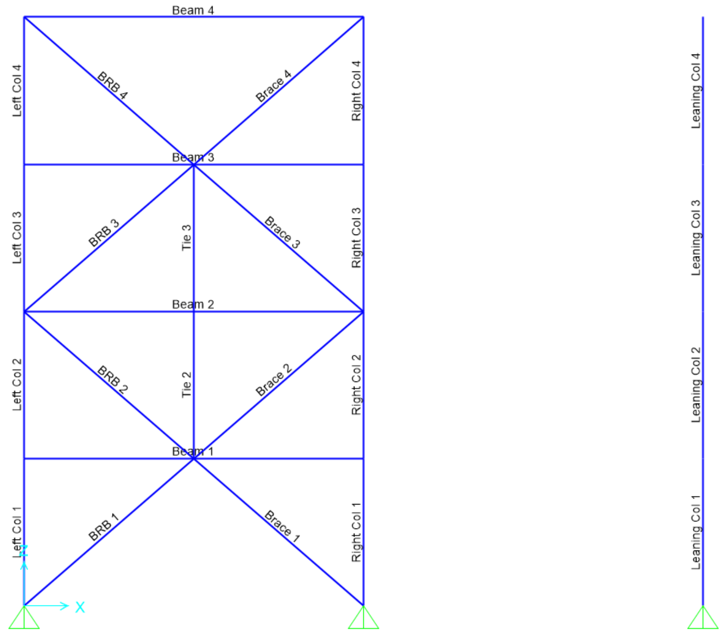

Figure 3.1: Example four-story frame model.

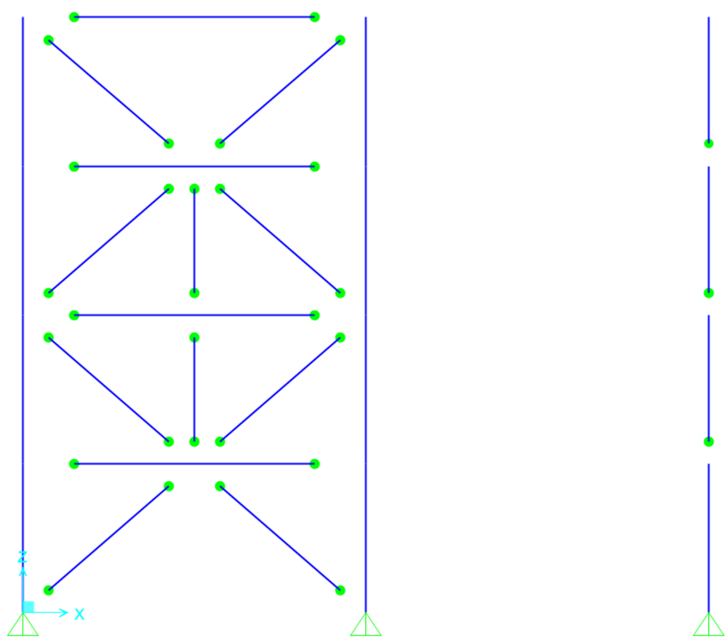

Figure 3.2: Connection detail of example four-story frame model.
Dots indicate pinned end connections.

Table 3.2: Archetype dead loads

Load source	Story load (kPa)	(psf)	Roof load (kPa)	(psf)
Decking	2.4	50	0.14	3
Structural framing	0.96	20	0.96	20
Miscellaneous	0.48	10	0.48	10
$\sum$	3.8	80	1.6	33

Table 3.3: Archetype live loads

Load source	Story load (kPa)	(psf)	Roof load (kPa)	(psf)
Office	2.4	50	—	—
Partitions	0.72	15	—	—
Roof	—	—	0.96	20
$\sum$	3.1	65	0.96	20

design phase could make the system being evaluated appear stronger than it actually is in application (FEMA 2009). Strongback systems potentially increase redundancy inherently, as they engage multiple stories of the lateral force resisting system. This feature is of interest to the broader structural engineering community (Panian et al. 2015), and further study is warranted.

3.2.1 Gravity load

The dead load on the structures consists of both horizontally- and vertically-distributed loads. For simplicity, the structural steel framing was represented by a "smeared" 0.96 kPa (20 psf) load. Each floor had a composite slab weighing 2.4 kPa (50 psf). Plain steel decking (0.14 kPa, 3 psf) was used instead for the roof. An additional 0.48 kPa (10 psf) was included at all levels to represent roofing, fireproofing, etc. The edges of the structures support walls weighing 1.2 kPa (25 psf). A 1.1 m (42 in.) parapet of the same weight runs the edge of the roof.

For the primary set of archetypes, an office live load of 2.4 kPa (50 psf) was used, with a partition live loading of 0.72 kPa (15 psf). For the very high gravity load archetypes, a warehouse loading of 12 kPa (250 psf) was used, with no provision for partitions. This warehouse loading was also considered storage for the purpose of seismic loading. The gravity loads are summarized in Tables 3.2 and 3.3.

Live load reduction was accomplished using the recommendations provided in Ziemian and McGuire (1992). Reduced live loads were directly applied to the models, with upward loads on the columns at each floor to represent the additional reduction due to the influence area of the columns. These correcting loads were estimated using the assumption that all gravity load was carried by the columns, instead of being split between the columns and the braces.

Table 3.4: FEMA P695 site-specific factors

Category	S_S (g)	S_1 (g)	S_{DS} (g)	S_{D1} (g)	T_s (s)
D_{max}	1.5	0.60[1]	1.0	0.60	0.60
D_{min}	0.55	0.132	0.50	0.20	0.40

[1] FEMA P695 specifies that this value is "rounded", and should be considered less than 0.60 when the difference is important—e.g. in Eq. (3.4).

3.2.2 Seismic load

Seismic loads were calculated using the equivalent lateral force method. Two levels of intensity, D_{max} and D_{min}, were considered. These levels, provided by FEMA P695, specify the range of ground motion intensities for structures within seismic design category (SDC) D. The corresponding site-specific factors S_1, S_{D1}, and S_{DS}, characterize the accelerations of the maximum-considered earthquake (MCE) as well as the design-level accelerations. Design-level accelerations are normally calculated from the mapped values using site-specific soil data, but instead the methodology provides specific intensities. The specified factors for D_{max} and D_{min} are listed in Table 3.4.

As SBFs have not been previously evaluated by the methodology, initial seismic performance factors must be used. For this work, the performance factors for buckling-restrained braced frames (BRBF) were used, with $R = 8$ and $C_d = 5.5$. The factors for the BRBF system are used because SBFs are expected to be highly ductile, and utilize BRBs as the primary energy-dissipating element. The importance factor, I_e, was set to 1.0, per FEMA P695.

For normal weight archetypes, the seismic weight W consists of the dead loads and a 0.48 kPa (10 psf) provision for partitions. For high gravity load archetypes, the seismic weight consists of the dead loads and the storage live load (specified by ASCE 7-16 as 25% of the standard live load), with no provision for partitions.

The seismic base shear, V, is calculated using Eq. (3.1).

$$V = C_s W \tag{3.1}$$

The seismic response coefficient, C_s, is given by Eq. (3.2).

$$C_s = \frac{S_{DS}}{R/I_e} \tag{3.2}$$

C_s is bounded by several values and requires the fundamental building period, T, calculated from Eq. (2.1). The maximum and minimum values for C_s are given by Eqs. (3.3) and (3.4) respectively. For structures with very long periods, ASCE 7-16 sets an additional bound on the maximum value; however, the methodology specifically disallows the inclusion of archetypes with such long periods, and the additional bound is not considered here.

$$C_{s,\max} = \frac{S_{D1}}{T\left(R/I_e\right)} \tag{3.3}$$

$$C_{s,\min} = \max\begin{cases} 0.01 \\ 0.044 S_{DS} I_e \\ 0.5 S_1 / \left(R/I_e\right) & \text{if } S_1 \geq 0.6\,\mathrm{g} \end{cases} \tag{3.4}$$

Where:

S_{DS}	=	Design spectral response acceleration parameter at short periods (g)
S_1	=	Mapped MCE[1] spectral response acceleration parameter at a period of 1.0 s (g)

Vertical distribution of the load was determined from Equations (3.5) and (3.6).

$$F_x = C_{vx} V \tag{3.5}$$

$$C_{vx} = \frac{w_x h_x^k}{\sum\limits_{i=1}^{n} w_i h_i^k} \tag{3.6}$$

Where:

F_x	=	Seismic force at level x, kN (kip)
C_{vx}	=	Vertical distribution factor (unitless)
w_i, w_x	=	Portion of seismic weight assigned to level i or x, kN (kip)
h_i, h_x	=	Height from the base of the structure to level i or x, m (ft)
k	=	$\begin{cases} 1 & T \leq 0.5\,\mathrm{s} \\ 0.5T + 0.75 & 0.5\,\mathrm{s} < T < 2.5\,\mathrm{s} \\ 2 & T \geq 2.5\,\mathrm{s} \end{cases}$ (unitless)

Rigid diaphragm behavior was assumed for all floors. Accidental torsion was not included, as ASCE 7-16 only requires it be considered when a horizontal irregularity is present. The regular building plan for all archetypes prevents the presence of a horizontal irregularity.

Vertical seismic loads were calculated using Eq. (3.7), and applied coincident with the corresponding dead loads in the direction of gravity.

$$E_v = 0.2 S_{DS} D \tag{3.7}$$

Where:

D	=	Dead load

[1] Maximum considered earthquake

3.3 Capacity design and modifications

The members of the SBF were also designed for capacity loads from the BRBs. Basic capacity design as described in AISC (2018) develops a pattern of loads in the energy-dissipating elements based on a first-mode response. The amplitude of these loads is defined by the expected capacity of the corresponding element. For BRBs, the expected capacity is the expected yield strength of the steel core, modified for strain hardening and adjusted for increases in compressive strength due to interaction between the core and the outer brace (AISC 2016a).

Capacity design provides a performance-based alternative to prescriptive overstrength values, which may not correctly represent the distribution of seismic loads. For strongbacks, however, basic first-mode capacity design inadequately describes the loads experienced during cyclical yielding of the energy-dissipating system (Simpson 2018). Higher mode effects must be accounted for, as the strongback itself imposes a first-mode displacement distribution, resisting and accumulating forces that would be expressed in higher modes of vibration.

Three alternative methods of capacity design are considered here: amplified, modal, and permutational. Designs using basic first-mode capacity provided a control system. Each method follows the same basic steps:

1. Identify the pattern of loads in the BRBs, noting the direction of axial forces (i.e. tension or compression).
2. Remove the BRBs from the model, replacing them with the appropriate expected capacity load in the direction from step 1.
3. Restore stability to the frame by pinning the left column at each floor, and run the analysis.

The difference between the methods primarily arises in step 1, though amplified capacity design modifies step 2.

3.3.1 Basic capacity design

Basic capacity design adapts the provisions for buckling-restrained braced frames from AISC 341-16. The expected strength in compression for BRBs is given by Eq. (3.8) (AISC 2016a):

$$F_{ec} = \beta\omega R_y F_{ysc} A_{sc} \tag{3.8}$$

Where:

β	=	Compression strength adjustment factor (unitless)
ω	=	Strain hardening adjustment factor (unitless)
$R_y F_{ysc}$	=	Expected yield strength of the BRB steel core, MPa (ksi)
A_{sc}	=	Cross-sectional area of the BRB steel core, mm^2 (in.^2)

Similarly, the expected strength in tension is given by Eq. (3.9):

$$F_{et} = \omega R_y F_{ysc} A_{sc} \tag{3.9}$$

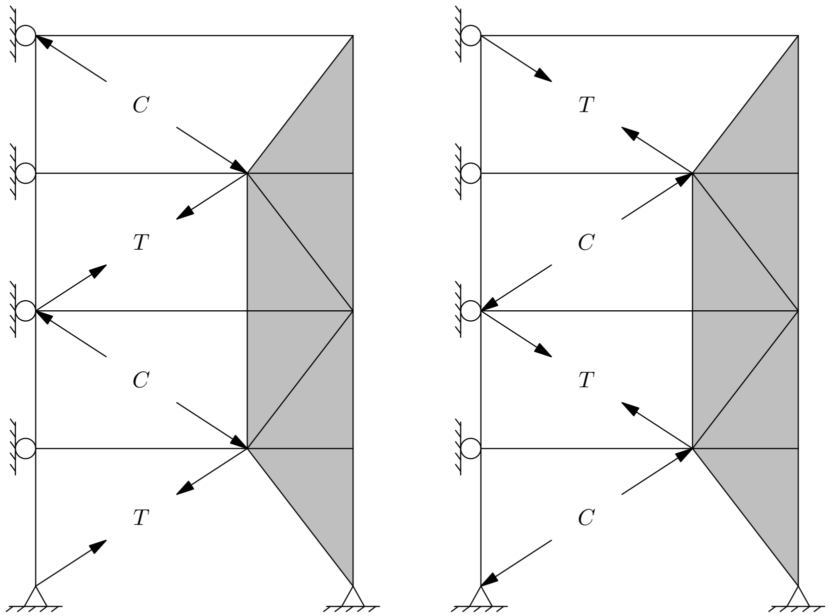

Figure 3.3: Capacity-limited load patterns for first-mode displacement.

Values of 1.1 and 1.4 were used for β and ω, respectively. In general, these values vary based on the BRB connections, angle, manufacturer, and specific design; as the models do not contain this specificity, the median expected values from NIST (2015) were used here.

Basic capacity design uses an assumed first-mode displacement to obtain the pattern of forces in the BRBs. This produces an alternating tension/compression pattern for X type bracing, while for chevron bracing the braces all act in the same direction. Fig. 3.3 shows an example of this first-mode loading. This pattern must also be considered in the reverse, giving two capacity patterns for basic capacity design.

3.3.2 Amplified capacity design

The simplest modification to capacity design is to amplify the calculated effects from Equations (3.8) and (3.9) by a constant factor. No new analysis of the BRB system need be performed, but careful consideration is needed to select a factor that is high enough to capture the effects missing from the first mode but not so high as to completely overdesign the system. For this thesis, amplified capacity design used a factor of 1.1. This factor was selected based on the already existing requirements in AISC (2016a) for connections in special concentrically-braced frames. This method is intended to provide the simplest means for overcoming the flaws of basic capacity design, and requires the same number of analyses.

3.3.3 Modal capacity design

Braced frames can be reasonably modeled as simple shear structures, with masses concentrated at each floor. For these structures, the number of modes is equal to the number of stories, producing at most $2n$ capacity

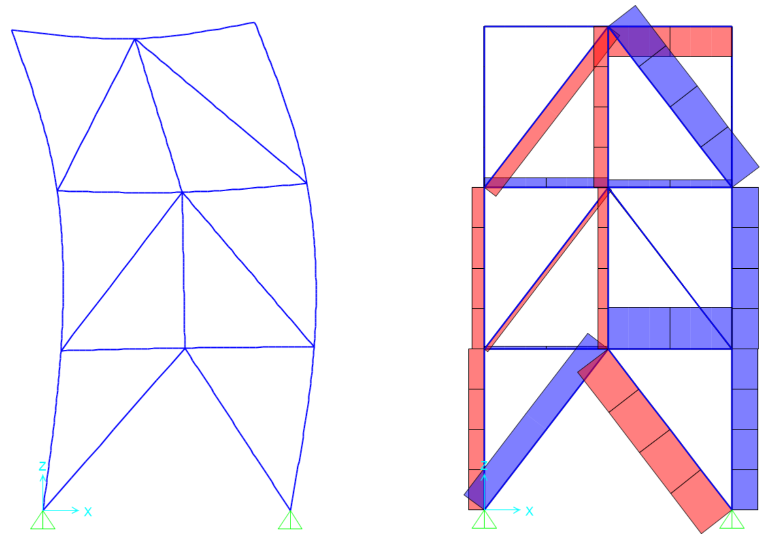

Figure 3.4: Second mode shape of frame.
Left: Displacement. Right: Axial loads.

effect patterns (allowing for braces to be in either tension or compression), where n is the number of stories. Modern analysis software is eminently capable of determining the required mode shapes.

Capacity design patterns up to the fourth mode were considered. For 2- and 3-story buildings, only up to the second and third modes, respectively, were considered. This results in $2n$ patterns, where n is the number of modes considered, each checked for the two capacity load combinations for a total of $4n$ cases. Initial design using standard load patterns was performed, followed by an eigenvalue analysis to determine the mode shape. The mode shape was then used to determine the appropriate direction for the capacity loads. For example, the second mode shape and corresponding axial force diagram for a three-story frame is shown in Fig. 3.4. Based on the axial forces, capacity load patterns were generated, with any amount of compression or tension being scaled to the maximum expected yield strength of the element.

3.3.4 Permutational capacity design

As an alternative to modal analysis, it is possible to generate the set of all possible permutations of capacity effect patterns. For a number of stories s, and considering braces to be either at maximum tension or maximum compression, this generates 2^s possible patterns of capacity loading, which must be checked for both capacity-limited load combinations, for a total of 2^{s+1} cases to analyze. For short structures this remains within feasibility for automated enveloping of analyses, but quickly becomes very computationally expensive: a two-story structure has only eight permutational cases to run, but a 9-story archetype frame has over 1000 different cases to run, and 44 non-capacity-limited members to check and optimize against those cases.

3.4 Design criteria

The design standards used for the archetypes and the relevant sections from those standards are summarized in Table 3.1. The equivalent lateral force method was used to obtain the seismic loads for all archetypes. A second-order direct analysis was used to obtain the required strengths.

3.4.1 Member strength

ASCE 7-16 provides two general methods for design of structures: strength design, also called load and resistance factor design (LRFD), and allowable stress design (ASD). This thesis uses LRFD throughout.

Required and available strengths for non-buckling-restrained members were calculated according to AISC 360-16 using the direct analysis method, with stiffness reduction (based on the $0.8\tau_b$ method) applied to all members. Beam strength and stiffness was calculated assuming no contribution from the composite floor system, with lateral point bracing provided at the midpoints between the columns and the tie braces. The available strength of buckling-restrained braces was calculated using the recommendations from AISC (2018). This assumes no buckling, with member strength based solely on the yield strength of the BRB core:

$$\phi P_{ysc} = \phi F_{ysc} A_{sc} \tag{3.10}$$

Where:

ϕ	=	0.90 (tension and compression)
P_{ysc}	=	Yield strength of BRB core
F_{ysc}	=	Design yield stress of BRB core
A_{sc}	=	Area of steel BRB core

Notional loads to represent imperfections according to AISC 360-16 were included in all gravity load combinations. Per section C2.2b(d) in AISC 360-16, notional loads are not required to be included in lateral load combinations if the ratio of maximum second-order to maximum first-order drift is less than or equal to 1.7 (AISC 2016a). Detailed results confirming these drifts are available in Table A.3. The following load combinations from ASCE 7-16 were used:

1. $1.4D$
2. $1.2D + 1.6L + 0.5L_r$
3. $1.2D + 1.6L_r + 0.5L$
4. $1.2D + E_v + E_h + 0.5L$
5. $0.9D - E_v + E_h$

Where:

D	=	Dead load
L	=	Live load
L_r	=	Roof live load
E_v	=	Vertical seismic load
E_h	=	Horizontal seismic load

For the archetypes designed with high gravity loads, the reduction of the live load factor to 0.5 no longer applied, and alternate versions of combinations 3 and 4 were used:

3. $1.2D + 1.6L_r + L$
4. $1.2D + E_v + E_h + L$

Additionally, capacity design combinations were considered, substituting E_{cl} for E_h in combinations 4 and 5, where E_{cl} is the capacity-limited horizontal seismic load effect.

For standard, non-capacity-limited loading, load combinations 1–5 were checked twice, once for each direction of lateral loading—notional loads for 1–3, and seismic loads for 4 and 5. The capacity-limited versions of 4 and 5 were checked for each pattern of loads generated by the various methods.

3.4.2 Seismic story drifts

Allowable and design story drifts were calculated according to ASCE 7-16. The allowable story drift, Δ_a, for each floor was calculated using Eq. (3.11), from ASCE 7-16 table 12.12-1 ("All other structures", for importance category II).

$$\Delta_a = 0.020 h_{sx} \tag{3.11}$$

Where:

h_{sx}	=	Story height below level x (in.)

Design story drift Δ_x was calculated using Eq. (3.12), derived from section 12.8.6 of ASCE 7-16. The deflections were calculated from load combinations 4 and 5 including geometric nonlinear effects.

$$\Delta_x = \frac{C_d}{I_e}\left(\delta_{xe} - \delta_{(x-1)e}\right) \tag{3.12}$$

Where:

δ_{xe}	=	Deflection at story x determined by elastic analysis, mm (in.)
$\delta_{(x-1)e}$	=	Deflection at story $x-1$ determined by elastic analysis, mm (in.)

The deflections used were those calculated along the column incorporated into the strongback.

3.4.3 Stability coefficient

The stability coefficient, θ, was calculated using Eq. (3.13) (ASCE 2016).

$$\theta = \frac{P_x \Delta_x I_e}{V_x h_{sx} C_d} \tag{3.13}$$

Where:

P_x	=	Total vertical design load at and above level x, kN (kip)
V_x	=	Story shear between levels x and $x-1$, kN (kip)

When calculating P_x, load combination 4 was used, with no load factors exceeding 1.0, following the guidance in the commentary to ASCE 7-16. As before, the 0.5 factor on L increases to 1.0 when the unreduced floor live load exceeds 4.78 kPa (100 psf).

4. $D + E_v + E_h + 0.5L$

The story shear V_x and story drift Δ_x are those corresponding to load combination 4, except that the drift was calculated using a first-order analysis for the stability check. The maximum stability coefficient $\theta_{\max}$ was calculated from Eq. (3.14):

$$\theta_{\max} = \frac{0.5}{\beta C_d} \leq 0.25 \tag{3.14}$$

Where:

β	=	Ratio of story shear demand to capacity between levels x and $x-1$ (unitless)

The shear demand ratio β was calculated by taking the maximum of the demand-to-capacity ratios of each element comprising the SBF on each floor. Fig. 3.5 shows an example of this, with members highlighted according to their controlling demands. On the second story, the circled element has the greatest value of 0.954, which is then used for β on that level.

3.4.4 Deflection limits

A vertical deflection limit of $\ell/360$ was imposed for all beams, where ℓ is the length of the beam between supports (ICC 2017). This limit was checked against the recommended service load combination from ASCE (2016):

6. $D + L$

3.4.5 Ductility requirements

The ductility requirements on section width-to-thickness ratios are mostly adopted from the provisions for buckling-restrained braced frames (BRBF) in AISC 341-16. Columns, following the requirements for BRBF, are moderately ductile. However, the beams are highly-ductile members, as they are expected to serve as the secondary energy dissipators. The strongback braces are only required to be moderately ductile, on the

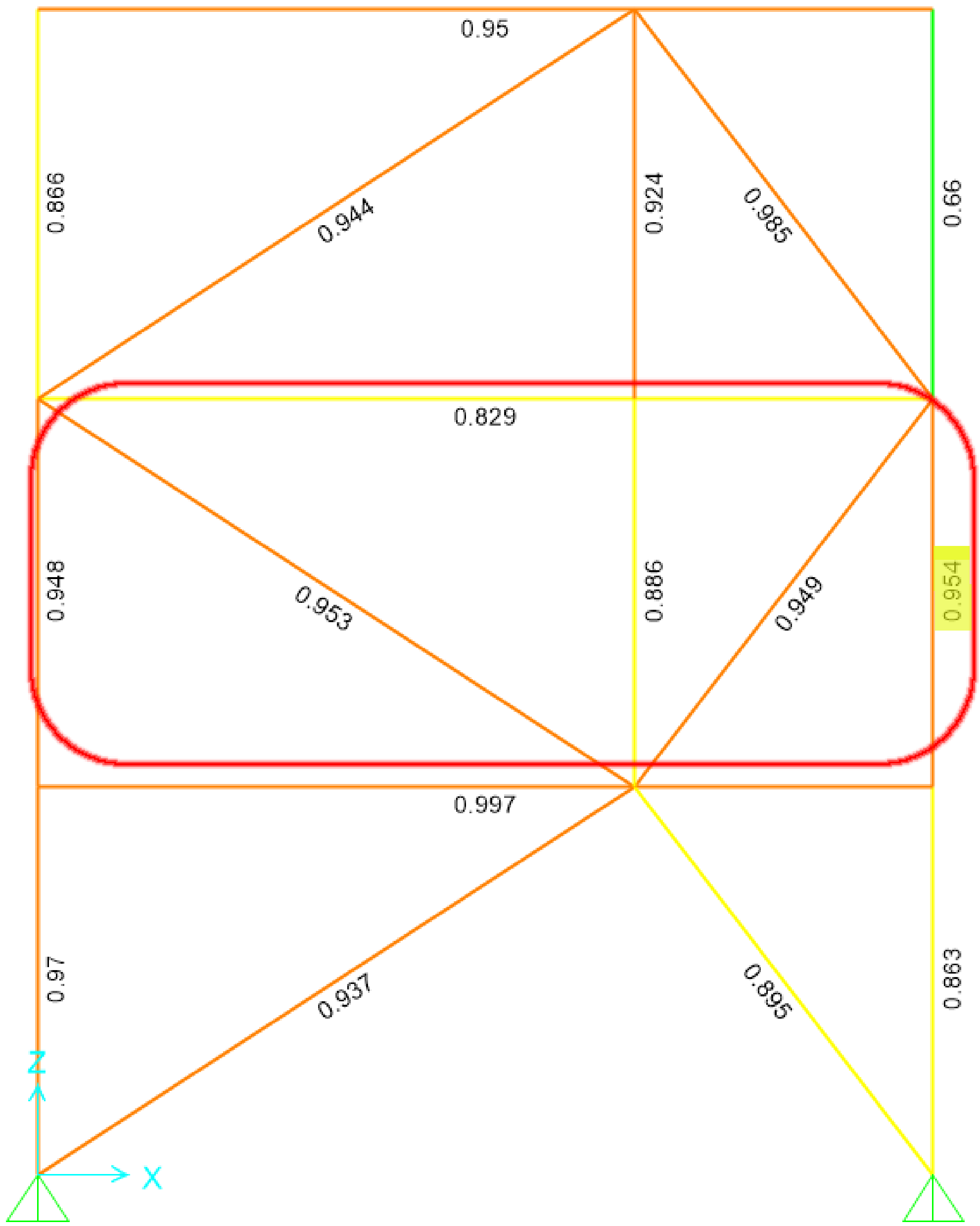

Figure 3.5: Strongback braced frame showing design interaction values.
Elements considered part of the second story are marked by the red box, and the highlighted value indicates the element with the largest interaction ratio at that story. This value is subsequently used for β in Eq. (3.14).

basis that since the strongback is intended to remain elastic, the members that comprise it do not need to be capable of the same level of inelastic deformation as the beams (Simpson and Mahin 2017).

The ductility requirements impose section slenderness limits for all members except the BRBs. For beams, they additionally impose requirements on the provided lateral bracing. For the purpose of these designs, lateral bracing was assumed to be provided at the midpoints between the ties and the columns, leading to a minimum minor-axis radius of gyration for the beams (AISC 2016a):

$$r_{y,\min} = \frac{L_b R_y F_y}{0.095E} \tag{3.15}$$

Where:

$r_{y,\min}$	=	Minimum minor-axis radius of gyration, mm (in.)
L_b	=	Unbraced length of the beam, m (in.)
E	=	Modulus of elasticity of the beam, GPa (ksi)
$R_y F_y$	=	Expected yield stress of the beam, MPa (ksi)

3.4.6 Sizing restrictions

For all archetypes, braces in the strongback were limited to hollow structural sections (HSS). Columns and beams are limited to wide-flange (W) sections. The energy-dissipating braces are all BRBs, with core areas from the 2$^{\text{nd}}$ edition *Seismic Design Manual* (AISC 2018). Column selection was limited to the W10, W12, and W14 shape series. Columns were considered to span two stories. Once selected, the columns in any particular frame were limited to one series; for example, the columns in archetype 4X-20-Dmax are all W14 series. Beams were not explicitly limited in the same fashion, though frequently the same section was used at each floor because of ductility requirements controlling over strength requirements. No such effort was made for strongback brace sizes.

3.5 Design process

Design of the archetypes was accomplished using the SAP2000 analysis and design program (Computers and Structures, Inc. 2017). SAP2000 provides both a graphical user interface (GUI) and an application programming interface (API). The API allows the user to interface with the program's functions using a programming language such as Python (Python Software Foundation 2018).

A Python package for automatically creating, analyzing, and designing numeric models of strongback braced frames was developed. This package provides the tools for rapid development of archetype frames. Loads, load combinations, joint locations, and other details are all calculated and created in Python and created using the SAP2000 API. This greatly streamlines the process of developing archetypes, allowing for rapid iteration and experimentation.

Design is largely automated. The user provides configuration details, which are used to create the geometry in SAP2000. This model is analyzed and member sizes selected by SAP2000 based on standard, non-capacity-limited loading. An initial ductility check was performed after this stage, updating members as necessary, and the column series to standardize on was selected. The resulting base design is then designed automatically for the four progressively more stringent capacity methods: basic, then amplified, then modal, then permutational. After completion of each capacity-based design, the design is verified against all limit states and flagged for manual follow-up if necessary.

Once the designs are complete, details about the designed archetypes are stored in plain text configuration files that can be easily read by other programs. This bypasses the proprietary SAP2000 model format, allowing the archetypes to be easily transferred to other, more specialized analysis systems like OpenSees (McKenna et al. 1999), which will be used in the next phase of this project.

Chapter 4

Designs and Observations

In total, 56 archetype frames were developed using the 4 different capacity methods for a total of 211 unique designs. The archetypes were designed first for standard, non-capacity limited loading, followed by the four capacity design methods using a semi-automated process described in Section 3.5. A complete listing of the member sizes for designed frames is available in the Appendix in Table A.1.

Four example designs are presented here: 2Xo-30-Dmax, 4Xo-30-Dmax, 6Xo-30-Dmax, and 9Xo-30-Dmax. These archetypes use offset x-bracing with 30 ft bay widths, designed for seismic design category D_{max}, from 2 to 9 stories. The member sizes in Table 4.1 are reported using US standard sizes, with buckling-restrained braces reported by their core area in in.^{2}.

4.1 Observations

Most of the structural framing is not affected by the alternative capacity design methods. The primary exceptions to this are the tie braces, with modal and permutational capacity design methods increasing the size of these braces. Shorter archetypes are largely unaffected by the different design methods: Table 4.1 shows that for very short archetypes, there may even be no difference between the designs produced.

4-story archetypes are more affected by the different design methods, though the differences remain minimal. Shown in Table 4.1, the most significant change is the increased size of the tie braces when designed using modal or permutational analysis. This reflects the increased demand in the spine under higher modes. The similarities between the modal and permutational capacity results indicate that loads outside of the first four modes have minimal effect for most structures, and the additional trouble of permutational design—large number of cases, increased analysis runtime—are not worth the effort.

The 6- and 9-story archetypes in Table 4.1 show that the differences between modal and permutational analyses become more pronounced with taller archetypes. The tie braces are more affected than the lateral braces, but a trend of increasing size exists for both.

For archetypes designed for D_{max} seismic loading, fundamental periods calculated from eigenvalues generally align closely with the FEMA P695 fundamental period equation (Eq. (2.1)) using the $C_t = 0.02$ value for "All

Table 4.1: Example archetype member sizes

Archetype	Story	Left Col.	Right Col.	Beam	Brace	Tie	BRB
2Xo-30-Dmax							
Basic	1	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×5/16	n/a	2.25
	2	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
Amplified	1	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×5/16	n/a	2.25
	2	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
Modal	1	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×5/16	n/a	2.25
	2	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
Permutation	1	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×5/16	n/a	2.25
	2	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
4Xo-30-Dmax							
Basic	1	W14×61	W14×61	W14×68	HSS8×8×1/2	n/a	5.5
	2	W14×61	W14×61	W14×68	HSS5-1/2×5-1/2×3/8	HSS3-1/2×3-1/2×1/4	4.25
	3	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×5/16	HSS3×3×3/16	3.0
	4	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	1.0
Amplified	1	W14×61	W14×61	W14×68	HSS8×8×1/2	n/a	5.5
	2	W14×61	W14×61	W14×68	HSS5-1/2×5-1/2×3/8	HSS3-1/2×3-1/2×1/4	4.25
	3	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×5/16	HSS3×3×3/16	3.0
	4	W14×30	W14×30	W14×68	HSS5×5×5/16	n/a	1.0
Modal	1	W14×61	W14×61	W14×68	HSS8×8×1/2	n/a	5.5
	2	W14×61	W14×61	W14×68	HSS5-1/2×5-1/2×3/8	HSS5-1/2×5-1/2×5/16	4.25
	3	W14×30	W14×30	W14×68	HSS5×5×5/16	HSS5×5×5/16	3.0
	4	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	1.0
Permutation	1	W14×61	W14×61	W14×68	HSS8×8×1/2	n/a	5.5
	2	W14×61	W14×61	W14×68	HSS5-1/2×5-1/2×3/8	HSS5-1/2×5-1/2×5/16	4.25
	3	W14×30	W14×30	W14×68	HSS5×5×5/16	HSS5×5×5/16	3.0
	4	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	1.0
6Xo-30-Dmax							
Basic	1	W14×109	W14×109	W14×68	HSS9×9×5/8	n/a	7.0
	2	W14×109	W14×109	W14×68	HSS6×6×3/8	HSS5×5×5/16	6.5
	3	W14×61	W14×61	W14×68	HSS7×7×1/2	HSS5×5×5/16	6.0
	4	W14×61	W14×61	W14×68	HSS5-1/2×5-1/2×3/8	HSS3-1/2×3-1/2×1/4	4.25
	5	W14×30	W14×30	W14×68	HSS5×5×5/16	HSS3×3×3/16	2.75
	6	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
Amplified	1	W14×109	W14×109	W14×68	HSS10×10×5/8	n/a	7.0
	2	W14×109	W14×109	W14×68	HSS6×6×1/2	HSS5-1/2×5-1/2×5/16	6.5
	3	W14×61	W14×61	W14×68	HSS7×7×1/2	HSS5×5×5/16	6.0
	4	W14×61	W14×61	W14×68	HSS5-1/2×5-1/2×3/8	HSS3-1/2×3-1/2×1/4	4.25
	5	W14×30	W14×30	W14×68	HSS5×5×5/16	HSS3×3×1/4	2.75
	6	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
Modal	1	W14×109	W14×109	W14×68	HSS10×10×5/8	n/a	7.0
	2	W14×109	W14×109	W14×68	HSS6×6×3/8	HSS7×7×1/2	6.5
	3	W14×61	W14×53	W14×68	HSS7×7×1/2	HSS6×6×5/8	6.0
	4	W14×61	W14×53	W14×68	HSS5-1/2×5-1/2×3/8	HSS5×5×5/16	4.5
	5	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	2.75
	6	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75

Table 4.1 (continued)

Archetype	Story	Left Col.	Right Col.	Beam	Brace	Tie	BRB
Permutation	1	W14×109	W14×109	W14×74	HSS10×10×5/8	n/a	7.0
	2	W14×109	W14×109	W14×68	HSS6×6×1/2	HSS7×7×1/2	6.5
	3	W14×61	W14×53	W14×68	HSS7×7×1/2	HSS7×7×1/2	6.0
	4	W14×61	W14×53	W14×68	HSS5-1/2×5-1/2×3/8	HSS5-1/2×5-1/2×5/16	4.75
	5	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	HSS5×5×5/16	2.75
	6	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
9Xo-30-Dmax							
Basic	1	W14×176	W14×159	W14×68	HSS10×10×3/4	n/a	8.0
	2	W14×176	W14×159	W14×68	HSS6×6×1/2	HSS6×6×1/2	7.5
	3	W14×120	W14×109	W14×68	HSS8×8×1/2	HSS6×6×1/2	7.0
	4	W14×120	W14×109	W14×68	HSS6×6×3/8	HSS5-1/2×5-1/2×3/8	7.0
	5	W14×74	W14×68	W14×68	HSS7×7×1/2	HSS5-1/2×5-1/2×5/16	6.0
	6	W14×74	W14×68	W14×68	HSS5-1/2×5-1/2×3/8	HSS4×4×1/4	5.5
	7	W14×38	W14×43	W14×68	HSS5-1/2×5-1/2×3/8	HSS4×4×1/4	4.0
	8	W14×38	W14×43	W14×68	HSS5×5×5/16	HSS3-1/2×3-1/2×1/4	2.0
	9	W14×22	W14×22	W14×68	HSS3-1/2×3-1/2×1/4	HSS2-1/4×2-1/4×3/16	0.75
Amplified	1	W14×176	W14×176	W14×68	HSS10×10×3/4	n/a	8.0
	2	W14×176	W14×176	W14×68	HSS7×7×1/2	HSS6×6×5/8	7.5
	3	W14×120	W14×109	W14×68	HSS8×8×5/8	HSS6×6×5/8	7.0
	4	W14×120	W14×109	W14×68	HSS6×6×3/8	HSS6×6×3/8	7.0
	5	W14×74	W14×74	W14×68	HSS7×7×1/2	HSS6×6×3/8	6.0
	6	W14×74	W14×74	W14×68	HSS5-1/2×5-1/2×3/8	HSS4×4×1/4	5.5
	7	W14×43	W14×43	W14×68	HSS6×6×3/8	HSS4×4×1/4	4.0
	8	W14×43	W14×43	W14×68	HSS5×5×5/16	HSS3-1/2×3-1/2×1/4	2.0
	9	W14×22	W14×22	W14×68	HSS3-1/2×3-1/2×1/4	HSS2-1/4×2-1/4×3/16	0.75
Modal	1	W14×176	W14×159	W14×68	HSS10×10×3/4	n/a	8.0
	2	W14×176	W14×159	W14×68	HSS7×7×1/2	HSS7×7×1/2	7.5
	3	W14×120	W14×109	W14×68	HSS8×8×5/8	HSS7×7×1/2	7.0
	4	W14×120	W14×109	W14×68	HSS5-1/2×5-1/2×3/8	HSS7×7×1/2	7.0
	5	W14×74	W14×61	W14×68	HSS7×7×1/2	HSS6×6×5/8	6.0
	6	W14×74	W14×61	W14×68	HSS6×6×3/8	HSS5-1/2×5-1/2×3/8	5.5
	7	W14×43	W14×43	W14×68	HSS5-1/2×5-1/2×5/16	HSS5-1/2×5-1/2×5/16	4.0
	8	W14×43	W14×43	W14×68	HSS5×5×5/16	HSS4×4×1/4	2.25
	9	W14×22	W14×22	W14×68	HSS4×4×1/4	HSS3-1/2×3-1/2×1/4	0.75
Permutation	1	W14×176	W14×176	W18×86	HSS12×12×3/4	n/a	8.0
	2	W14×176	W14×176	W14×68	HSS7×7×1/2	HSS9×9×5/8	7.5
	3	W14×120	W14×109	W14×74	HSS8×8×1/2	HSS9×9×5/8	7.0
	4	W14×120	W14×109	W14×68	HSS6×6×1/2	HSS8×8×5/8	7.0
	5	W14×74	W14×61	W14×68	HSS7×7×1/2	HSS8×8×5/8	6.0
	6	W14×74	W14×61	W14×68	HSS6×6×3/8	HSS6×6×1/2	5.5
	7	W14×43	W14×38	W14×68	HSS5×5×5/16	HSS6×6×1/2	4.0
	8	W14×43	W14×38	W14×68	HSS5×5×5/16	HSS4×4×5/16	2.5
	9	W14×22	W14×22	W14×68	HSS3-1/2×3-1/2×1/4	HSS3-1/2×3-1/2×1/4	0.75

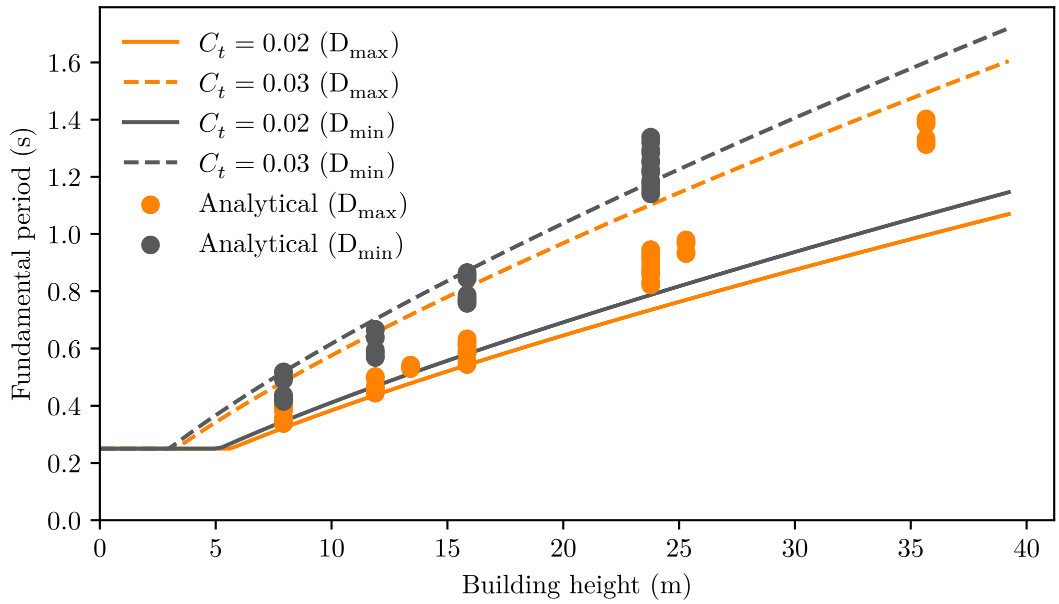

Figure 4.1: Estimated and actual fundamental periods.

other structures" from ASCE 7-16—see Fig. 4.1. Results indicate, however, that archetypes designed for D_{min} more closely align with period values calculated using the $C_t = 0.03$ approximation for buckling-restrained braced frames. $C_t = 0.02$ was used for all designs presented in this study; further investigation is necessary to determine if a different value of C_t should be used for archetype design.

There is a general trend where as more capacity patterns are considered, a greater amount of steel framing is required, but this trend is small and most clearly expressed in the 9-story archetypes. This can be seen in Figs. 4.2 and 4.3, as well as Table A.2. Shorter archetypes often experienced no change in the structural framing—though this may also be expected, as shorter archetypes are subject to fewer modes of vibration.

The relatively modest changes in required framing suggest that, while performance objectives still need to evaluated, these design methodologies are plausible for use in practice. They do not produce severely over-designed frames, and the increase in tie size reflects an existing observation that strongback braced frames experience significant higher-mode effects, loading the structure in ways not accounted for by current design practices.

4.1.1 Controlling criteria

Strength and ductility limits controlled all components in all designs.

The buckling-restrained braces are designed based on the standard lateral load combinations, and are largely unaffected by the differences between the capacity design procedures. Largely the same sizes are produced by the various methods, with a slight trend is observed in the taller archetypes designed under permutational analysis, with BRBs near the roof being larger than those designed under different methods, but Fig. 4.3

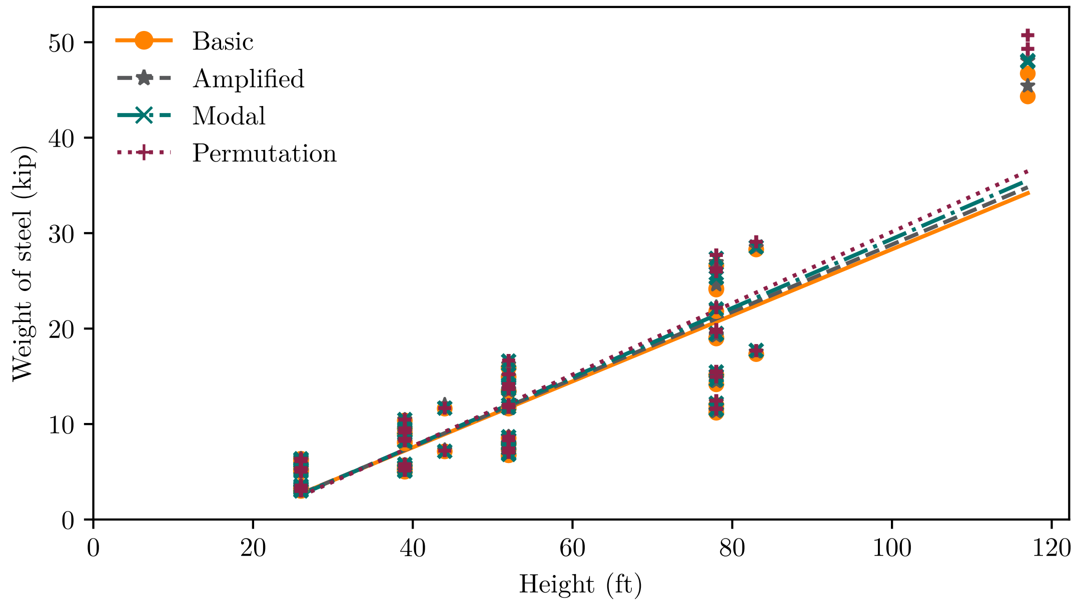

Figure 4.2: Steel weight vs. archetype height.
Each point represents the results from a single designed frame. Linear regression was used to determine the best-fit lines.

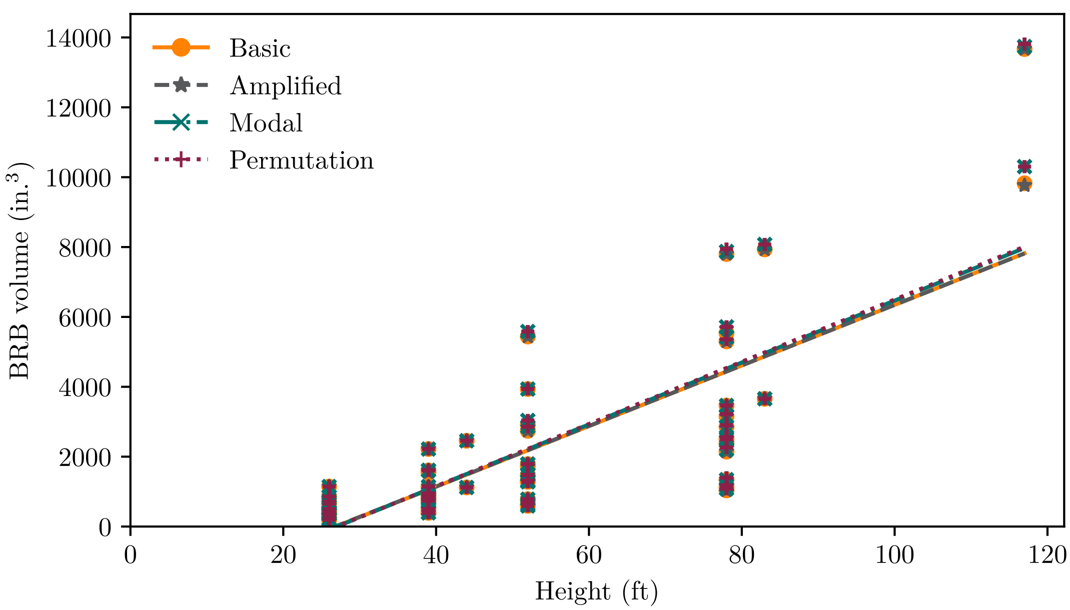

Figure 4.3: BRB volume vs. archetype height.
Each point represents the results from a single designed frame. Linear regression was used to determine the best-fit lines.

shows that the general trend in BRB height is largely unaffected by design method.

Beams in the archetypes were found to be primarily controlled by ductility requirements, which enforced a required minor-axis radius of gyration based on assumed unbraced length and compactness requirements affected by the level of axial load. This frequently resulted in the same section being used at all stories, with some taller archetypes requiring larger first-story beams. Column sizes are largely controlled either by the standard load combinations or first-mode capacity loads. Some higher-story columns were controlled by higher modes, but overall there was minimal change between the different design methods.

Tie braces not controlled by capacity combinations were controlled by gravity loads; gravity-controlled ties mostly occur in those archetypes designed by basic and amplified capacity design. Ties were the most significantly affected by modal and permutational analysis, with the greater differences observed as archetype height increased. Lateral braces in the strongback were largely unaffected by higher-mode analysis, with almost all braces controlled by first-mode capacity loading. Amplified capacity analysis had the largest effect on the design of the lateral braces.

Drift and stability did not control any designs. Even with the relatively high C_d factor, the static analyses required by ASCE (2016) indicate that the design methods are successful in producing very stiff frames; further analysis is needed to verify that desired stiffnesses are met.

4.2 Utility of design methods

For many archetypes, the designs remain largely unchanged between the different design methods, especially for very short archetypes. Differences appear largely in the tie braces for mid-height archetypes, with greater changes to the structural framing in the 6- and 9-story archetypes.

The amplified design method requires a further evaluation of the factor used to amplify the analyses, as the results differ little from those produced by basic capacity analysis. An additional concern with amplified analysis is that, as the pattern of loading is unchanged from basic analysis, the tie braces that act to form the strongback truss remain controlled by gravity loads and not, as expected, the capacity requirements.

The time required to run the automated design process is minimal for most frames; 6-story archetypes take 8–10 minutes to process, while 2-story ones are finished in less than a minute. The exponential nature of the permutational procedure makes it impractical as the number of stories increases: 9-story archetypes have over 1000 permutational capacity cases, and 44 members to check every time a capacity analysis is performed, increasing the initial design time to over an hour.

Chapter 5

Conclusions

Strongback braced frames (SBF) are a potential solution to the problem of steel braced frame damage concentration and residual drift. As a kind of elastic spine frame, they distribute loads across the height of the structure, preventing weak stories and reducing story drifts in general. However, seismic performance factors have not been developed for these systems, and existing methods for addressing system overstrength do not address the actual behavior of the frame.

The current standard for handling overstrength, capacity design, only considers the capacity-limited effects in a first-mode pattern. For most systems, this is sufficient to describe the loads present. SBF are subject to significant loads from higher modes, however, as the strongback remains elastic, distributing forces and enforcing a near-first mode deformation on the structure.

The lack of established seismic performance factors, as well as the limitations of basic first-mode capacity design, mean that SBF systems are not currently permitted under ASCE 7-16 to be designed using the equivalent lateral force (ELF) method, the predominant method for seismic design in the United States. It is thus desirous to develop seismic performance factors usable with the ELF method, and to remedy the issues with capacity design.

This thesis presents a preliminary study that provides a designed set of archetypes suitable for use in a study using the FEMA P695 methodology to determine the seismic performance factors for strongback braced frames. The methodology requires the selection of archetype system configurations, which represent the width and breadth of the design space. 56 archetype SBF configurations were selected for this study, and account for expected variations in brace configuration, building height, gravity and seismic loading, and other parameters in the SBF design space.

This work additionally develops and considers three alternative methods of capacity design: amplified, modal, and permutational. Amplified capacity design takes the forces from basic capacity design and amplifies them by a constant factor. Modal capacity design performs a modal eigenvalue analysis and uses the resulting mode shapes to determine the loading patterns. Permutational capacity design considers all mathematically possible patterns of loading, whether or not they correspond to a mode of vibration. The archetype set was designed using each of these methods, as well as by basic first-mode capacity design as a control.

Design of these frames was accomplished using a semi-automated approach. A software package, written in Python and integrated with the SAP2000 application programming interface (API), was developed to provide automatic creation, analysis, design, and verification of archetype frames. Initial designs according to each method were developed by the software to satisfy strength limit states, using the SAP2000 member size optimization routines. These initial designs were then verified and adjusted manually for the remaining limit states.

Designing the archetypes according to the four different design methods produced 211 unique designs; 2-story modal and permutational analyses result in the same load patterns being analyzed. These designs will be evaluated in the next phase of this research to determine the ability of the design methods to achieve the desired performance goals, as well as determine the appropriate seismic performance factors for SBF.

Initial eigenvalue analyses were performed to determine the appropriate fundamental period for use with SBF. These analyses indicate that SBF designed according to the methods in this thesis are generally stiffer than corresponding buckling-restrained braced frames, but new coefficients for use with the approximate fundamental period equations from ASCE 7-16 may need to be developed.

Strength and ductility limits controlled all components in all designs. Drift and stability coefficient limits did not control the design of frames, an indicator that the design methods are capable of producing structures that meet desired stiffness goals.

The alternative design methods resulted in modest differences in steel weight, providing preliminary indication that the methods are reasonable and not highly conservative.

Amplified capacity design does not, in general, result in significantly different structures than the use of basic capacity design. This may be due to the factor used in this study, but in particular the lack of change in the size of tie braces, compared to modal and permutational design, indicates an issue with the loading pattern.

Permutational capacity design appears to be relatively inefficient. For tall structures, the method is impractical as the time required for the analysis increases exponentially with the number of stories. For short structures, the differences between modal and permutational design are minimal, as there are not significantly more patterns of loading beyond the four mode shapes considered.

Modal capacity design is the most promising. The resulting designs feature largely strengthened tie braces, which are responsible for linking the stories of the frame together and improving the distribution of forces throughout the system.

5.1 Next steps

Most critically, these designs must be analyzed under dynamic loads, and their response evaluated. To that end, the next phase of this research will involve modeling of these frames in OpenSees, an open-source earthquake engineering simulation program (McKenna et al. 1999). Two-dimensional models with distributed plasticity will be used, with connection design based on Roeder et al. (2011).

These models will be used to perform a FEMA P695-compliant study of the seismic performance factors used in the design of these frames, and to evaluate the ability of the design methods to achieve the desired performance goals: namely, minimizing damage concentration and residual drifts.

Of particular note for close study is the behavior of the tie braces that connect the stories of the strongback together. These braces were the most significantly affected by incorporating loads from higher modes; this is expected based on prior studies of strongback behavior, which indicate that strongbacks must resist loads from multiple modes of vibration. The sizing of these ties may be the important step from basic capacity design to a capacity design method that incorporates the necessary loads.

A potential concern resulting from these initial designs is the ability of the beams in the system to behave as secondary energy dissipators. The elastic model used for designing the archetypes used pinned connections for the beam-column connections; while this is a common idealization in design, the connections are actually semi-rigid, stiffened by the braces framing into the columns at the same location (Roeder et al. 2011). The ductility requirements are intended to mitigate or resolve this issue, but further analysis is necessary.

5.2 Further research

Several avenues remain for investigation of the behavior of strongback braced frames.

Additional configurations have been proposed for strongback braced frames that were not included in this study. These include a single energy dissipator configuration, where only a single buckling-restrained brace or similar device at ground level is used for energy dissipation (Lai and Mahin 2014), and placing the strongback spine external to the frame itself, as investigated in Zaruma and Fahnestock (2018).

The factor used for amplified capacity design needs evaluation for sensitivity; the factor used in this study was selected based on the requirements for connections in special concentrically-braced frames, but the minimal impact on the resulting designs indicates that a higher factor may be needed. The lack of impact on the size of the tie braces, compared to modal and permutational design, may also indicate that simply amplifying the first mode loading is insufficient, regardless of the factor used.

Other alternative methods of capacity design can be investigated. One option would be to combine the modal and amplified capacity methods, gaining the improvements to load pattern from the modal combinations and an additional factor of safety from the amplified loads.

For all frames, further investigation into the effects of the deflection amplification factor, C_d, is warranted. The value of C_d used in this project is the same used for buckling-restrained braced frames, but the eigenvalue analyses and lack of drift-controlled archetypes indicates that this value may be too high for strongback braced frames. Beyond braced frames, further research into the general effects of using a C_d value equal to R is necessary. C_d is the primary controller of the seismic story drift limit state, and advances in steel design and materials have pushed toward more ductile, more flexible systems. Allowing ductility while restraining flexibility is an important challenge, and elastic spine frames are a promising way to do just that.

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Appendix

The naming convention for archetypes is as follows:

```
<number of stories><configuration>-<bay width (ft)>-<seismic design category>[-<special>]
```

For example, archetype 2Xo-30-Dmax-Heavy has two (2) stories, has bracing in the Xo configuration (see Fig. 2.1), has 30 ft bays, is designed for seismic design category D_{max}, and uses the special higher gravity load setup.

Member sizes are reported in Table A.1 using US standard sizes. Buckling-restrained braces are reported by their core area in $in.^2$. Base shear, steel weight, and buckling-restrained brace volume are reported on a per-frame basis in Table A.2.

Table A.3 contains story drift ratios and the ratios of first-to-second-order drift needed to verify the dropping of notional loads from the lateral load combinations. The story drift ratios are given in percentages, calculated by taking the story drift and dividing by the height of the corresponding story.

Table A.4 contains the periods of each archetype, according to both FEMA P695 (fundamental period only) and the eigenvalue analyses performed within SAP2000.

Table A.1: Archetype member sizes

Archetype	Story	Left Col.	Right Col.	Beam	Brace	Tie	BRB
2C-20-Dmax							
Basic	1	W14×22	W14×26	W12×35	HSS5×5×5/16	n/a	1.25
	2	W14×22	W14×26	W12×35	HSS4×4×1/4	HSS2-1/4×2-1/4×3/16	0.5
Amplified	1	W14×26	W14×26	W12×35	HSS5×5×5/16	n/a	1.25
	2	W14×26	W14×26	W12×35	HSS4×4×1/4	HSS2-1/2×2-1/2×3/16	0.5
Modal	1	W14×26	W14×26	W12×35	HSS5×5×5/16	n/a	1.25
	2	W14×26	W14×26	W12×35	HSS4×4×1/4	HSS3-1/2×3-1/2×1/4	0.5
Permutation	1	W14×26	W14×26	W12×35	HSS5×5×5/16	n/a	1.25
	2	W14×26	W14×26	W12×35	HSS4×4×1/4	HSS3-1/2×3-1/2×1/4	0.5
2C-20-Dmin							
Basic	1	W14×22	W14×22	W12×35	HSS4×4×5/16	n/a	0.75
	2	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS2-1/4×2-1/4×3/16	0.25
Amplified	1	W14×22	W14×22	W12×35	HSS4-1/2×4-1/2×5/16	n/a	0.75
	2	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS2-1/4×2-1/4×3/16	0.25
Modal	1	W14×22	W14×22	W12×35	HSS4-1/2×4-1/2×5/16	n/a	0.75
	2	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	0.25
Permutation	1	W14×22	W14×22	W12×35	HSS4×4×5/16	n/a	0.75
	2	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	0.25
2C-30-Dmax							
Basic	1	W14×30	W14×30	W12×45	HSS6×6×3/8	n/a	2.25
	2	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	HSS3×3×3/16	0.75
Amplified	1	W14×30	W14×30	W12×45	HSS6×6×1/2	n/a	2.25
	2	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	HSS3×3×1/4	0.75
Modal	1	W14×30	W14×30	W12×45	HSS6×6×3/8	n/a	2.25
	2	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	HSS4×4×1/4	0.75
Permutation	1	W14×30	W14×30	W12×45	HSS6×6×3/8	n/a	2.25
	2	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	HSS4×4×1/4	0.75
2C-30-Dmin							
Basic	1	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	1.25
	2	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	HSS2-1/2×2-1/2×3/16	0.5
Amplified	1	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	1.25
	2	W14×30	W14×30	W12×45	HSS5×5×5/16	HSS2-1/2×2-1/2×3/16	0.5
Modal	1	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	1.25
	2	W14×30	W14×30	W12×45	HSS5×5×5/16	HSS3-1/2×3-1/2×1/4	0.5
Permutation	1	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	1.25
	2	W14×30	W14×30	W12×45	HSS5×5×5/16	HSS3-1/2×3-1/2×1/4	0.5
2X-20-Dmax							
Basic	1	W14×26	W14×26	W12×35	HSS5×5×5/16	n/a	1.25
	2	W14×26	W14×26	W18×35	HSS4×4×1/4	n/a	0.5
Amplified	1	W14×26	W14×26	W12×35	HSS5×5×5/16	n/a	1.25
	2	W14×26	W14×26	W18×35	HSS4×4×1/4	n/a	0.5
Modal	1	W14×26	W14×26	W12×35	HSS5×5×5/16	n/a	1.25

Table A.1 (continued)

Archetype	**Story**	**Left Col.**	**Right Col.**	**Beam**	**Brace**	**Tie**	**BRB**
	2	W14×26	W14×26	W18×35	HSS4×4×1/4	n/a	0.5
Permutation	1	W14×26	W14×26	W12×35	HSS5×5×5/16	n/a	1.25
	2	W14×26	W14×26	W18×35	HSS4×4×1/4	n/a	0.5
2X-20-Dmin							
Basic	1	W14×22	W14×22	W18×35	HSS4-1/2×4-1/2×5/16	n/a	0.75
	2	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	n/a	0.25
Amplified	1	W14×22	W14×22	W18×35	HSS4-1/2×4-1/2×5/16	n/a	0.75
	2	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	n/a	0.25
Modal	1	W14×22	W14×22	W12×35	HSS4-1/2×4-1/2×5/16	n/a	0.75
	2	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	n/a	0.25
Permutation	1	W14×22	W14×22	W12×35	HSS4-1/2×4-1/2×5/16	n/a	0.75
	2	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	n/a	0.25
2X-30-Dmax							
Basic	1	W14×30	W14×30	W12×45	HSS6×6×3/8	n/a	2.0
	2	W14×30	W14×30	W12×45	HSS5×5×5/16	n/a	0.75
Amplified	1	W14×30	W14×30	W12×45	HSS6×6×1/2	n/a	2.25
	2	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	0.75
Modal	1	W14×30	W14×30	W12×45	HSS6×6×3/8	n/a	2.0
	2	W14×30	W14×30	W12×45	HSS5×5×5/16	n/a	0.75
Permutation	1	W14×30	W14×30	W12×45	HSS6×6×3/8	n/a	2.0
	2	W14×30	W14×30	W12×45	HSS5×5×5/16	n/a	0.75
2X-30-Dmin							
Basic	1	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	1.25
	2	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	n/a	0.5
Amplified	1	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	1.25
	2	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	n/a	0.5
Modal	1	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	1.25
	2	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	n/a	0.5
Permutation	1	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	1.25
	2	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	n/a	0.5
2Xo-20-Dmax							
Basic	1	W14×22	W14×26	W12×45	HSS4-1/2×4-1/2×5/16	n/a	1.25
	2	W14×22	W14×26	W12×45	HSS3-1/2×3-1/2×1/4	n/a	0.5
Amplified	1	W14×26	W14×26	W12×45	HSS4-1/2×4-1/2×5/16	n/a	1.25
	2	W14×26	W14×26	W12×45	HSS3-1/2×3-1/2×1/4	n/a	0.5
Modal	1	W14×26	W14×26	W12×45	HSS4-1/2×4-1/2×5/16	n/a	1.25
	2	W14×26	W14×26	W12×45	HSS3-1/2×3-1/2×1/4	n/a	0.5
Permutation	1	W14×26	W14×26	W12×45	HSS4-1/2×4-1/2×5/16	n/a	1.25
	2	W14×26	W14×26	W12×45	HSS3-1/2×3-1/2×1/4	n/a	0.5
2Xo-20-Dmin							
Basic	1	W14×22	W14×22	W12×45	HSS4×4×1/4	n/a	0.75
	2	W14×22	W14×22	W12×45	HSS3×3×3/16	n/a	0.25

Table A.1 (continued)

Archetype	Story	Left Col.	Right Col.	Beam	Brace	Tie	BRB
Amplified	1	W14×22	W14×22	W12×45	HSS4×4×1/4	n/a	0.75
	2	W14×22	W14×22	W12×45	HSS3×3×1/4	n/a	0.25
Modal	1	W14×22	W14×22	W12×45	HSS4×4×1/4	n/a	0.75
	2	W14×22	W14×22	W12×45	HSS3×3×1/4	n/a	0.25
Permutation	1	W14×22	W14×22	W12×45	HSS4×4×1/4	n/a	0.75
	2	W14×22	W14×22	W12×45	HSS3×3×3/16	n/a	0.25
2Xo-30-Dmax							
Basic	1	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×5/16	n/a	2.25
	2	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
Amplified	1	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×5/16	n/a	2.25
	2	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
Modal	1	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×5/16	n/a	2.25
	2	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
Permutation	1	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×5/16	n/a	2.25
	2	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
2Xo-30-Dmax-Heavy							
Basic	1	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×3/8	n/a	3.25
	2	W14×30	W14×30	W14×68	HSS5×5×5/16	n/a	0.75
Amplified	1	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×3/8	n/a	3.25
	2	W14×30	W14×30	W14×68	HSS5×5×5/16	n/a	0.75
Modal	1	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×3/8	n/a	3.25
	2	W14×30	W14×30	W14×68	HSS5×5×5/16	n/a	0.75
Permutation	1	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×3/8	n/a	3.25
	2	W14×30	W14×30	W14×68	HSS5×5×5/16	n/a	0.75
2Xo-30-Dmin							
Basic	1	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	1.25
	2	W14×30	W14×30	W14×68	HSS4×4×1/4	n/a	0.5
Amplified	1	W14×30	W14×30	W14×68	HSS5×5×5/16	n/a	1.25
	2	W14×30	W14×30	W14×68	HSS4×4×1/4	n/a	0.5
Modal	1	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	1.25
	2	W14×30	W14×30	W14×68	HSS4×4×1/4	n/a	0.5
Permutation	1	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	1.25
	2	W14×30	W14×30	W14×68	HSS4×4×1/4	n/a	0.5
3C-20-Dmax							
Basic	1	W14×30	W14×30	W12×35	HSS5-1/2×5-1/2×3/8	n/a	2.0
	2	W14×30	W14×30	W12×35	HSS4-1/2×4-1/2×5/16	HSS2-1/2×2-1/2×3/16	1.25
	3	W14×22	W14×22	W18×35	HSS4×4×1/4	HSS2-1/2×2-1/2×3/16	0.5
Amplified	1	W14×30	W14×30	W12×35	HSS5-1/2×5-1/2×3/8	n/a	2.0
	2	W14×30	W14×30	W12×35	HSS5×5×5/16	HSS2-1/2×2-1/2×3/16	1.25
	3	W14×22	W14×22	W18×35	HSS4×4×1/4	HSS2-1/2×2-1/2×3/16	0.5
Modal	1	W14×30	W14×30	W12×35	HSS5-1/2×5-1/2×3/8	n/a	2.0
	2	W14×30	W14×30	W12×35	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	1.25

Table A.1 (continued)

Archetype	**Story**	**Left Col.**	**Right Col.**	**Beam**	**Brace**	**Tie**	**BRB**
	3	W14×22	W14×22	W12×35	HSS4×4×1/4	HSS3×3×1/4	0.5
Permutation	1	W14×30	W14×30	W12×35	HSS5-1/2×5-1/2×3/8	n/a	2.0
	2	W14×30	W14×30	W12×35	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	1.25
	3	W14×22	W14×22	W12×35	HSS4×4×1/4	HSS3-1/2×3-1/2×1/4	0.5
3C-20-Dmin							
Basic	1	W14×30	W14×30	W18×35	HSS4-1/2×4-1/2×5/16	n/a	1.0
	2	W14×30	W14×30	W18×35	HSS4×4×1/4	HSS2-1/4×2-1/4×3/16	0.75
	3	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS2-1/4×2-1/4×3/16	0.25
Amplified	1	W14×30	W14×30	W12×35	HSS5×5×5/16	n/a	1.0
	2	W14×30	W14×30	W18×35	HSS4×4×5/16	HSS2-1/4×2-1/4×3/16	0.75
	3	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS2-1/4×2-1/4×3/16	0.25
Modal	1	W14×30	W14×30	W12×35	HSS5×5×5/16	n/a	1.0
	2	W14×30	W14×30	W12×35	HSS4×4×1/4	HSS4×4×1/4	0.75
	3	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	0.25
Permutation	1	W14×30	W14×30	W12×35	HSS5×5×5/16	n/a	1.0
	2	W14×30	W14×30	W12×35	HSS4×4×1/4	HSS4×4×1/4	0.75
	3	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS3×3×1/4	0.25
3C-30-Dmax							
Basic	1	W14×43	W14×43	W12×45	HSS7×7×1/2	n/a	3.5
	2	W14×43	W14×43	W12×45	HSS6×6×1/2	HSS3-1/2×3-1/2×1/4	2.25
	3	W14×22	W14×22	W12×45	HSS5-1/2×5-1/2×5/16	HSS3×3×1/4	0.75
Amplified	1	W14×43	W14×43	W12×45	HSS7×7×1/2	n/a	3.5
	2	W14×43	W14×43	W12×45	HSS6×6×1/2	HSS3-1/2×3-1/2×1/4	2.25
	3	W14×22	W14×22	W12×45	HSS5-1/2×5-1/2×5/16	HSS3-1/2×3-1/2×1/4	0.75
Modal	1	W14×43	W14×43	W12×45	HSS7×7×1/2	n/a	3.75
	2	W14×43	W14×43	W12×45	HSS6×6×1/2	HSS5-1/2×5-1/2×5/16	2.25
	3	W14×22	W14×22	W12×45	HSS5-1/2×5-1/2×5/16	HSS3-1/2×3-1/2×1/4	0.75
Permutation	1	W14×43	W14×43	W12×45	HSS7×7×1/2	n/a	3.75
	2	W14×43	W14×43	W12×45	HSS6×6×1/2	HSS5-1/2×5-1/2×5/16	2.25
	3	W14×22	W14×22	W12×45	HSS5-1/2×5-1/2×5/16	HSS4×4×5/16	0.75
3C-30-Dmin							
Basic	1	W14×34	W14×38	W12×45	HSS6×6×3/8	n/a	2.0
	2	W14×34	W14×38	W12×45	HSS5-1/2×5-1/2×5/16	HSS3×3×1/4	1.0
	3	W14×22	W14×22	W12×45	HSS4-1/2×4-1/2×5/16	HSS2-1/2×2-1/2×3/16	0.5
Amplified	1	W14×34	W14×38	W12×45	HSS6×6×1/2	n/a	2.0
	2	W14×34	W14×38	W12×45	HSS5-1/2×5-1/2×5/16	HSS3×3×1/4	1.0
	3	W14×22	W14×22	W12×45	HSS4-1/2×4-1/2×5/16	HSS2-1/2×2-1/2×3/16	0.5
Modal	1	W14×34	W14×38	W12×45	HSS6×6×1/2	n/a	2.0
	2	W14×34	W14×38	W12×45	HSS5-1/2×5-1/2×5/16	HSS4-1/2×4-1/2×5/16	1.0
	3	W14×22	W14×22	W12×45	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	0.5
Permutation	1	W14×34	W14×38	W12×45	HSS6×6×5/8	n/a	2.25
	2	W14×34	W14×38	W12×45	HSS5-1/2×5-1/2×5/16	HSS4-1/2×4-1/2×5/16	1.0
	3	W14×22	W14×22	W12×45	HSS4-1/2×4-1/2×5/16	HSS3-1/2×3-1/2×1/4	0.5

Table A.1 (continued)

Archetype	**Story**	**Left Col.**	**Right Col.**	**Beam**	**Brace**	**Tie**	**BRB**
3X-20-Dmax							
Basic	1	W14×30	W14×30	W18×35	HSS6×6×3/8	n/a	2.25
	2	W14×30	W14×30	W18×35	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	1.25
	3	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS2-1/4×2-1/4×3/16	0.5
Amplified	1	W14×30	W14×30	W12×35	HSS6×6×1/2	n/a	2.25
	2	W14×30	W14×30	W18×35	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	1.25
	3	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS2-1/4×2-1/4×3/16	0.5
Modal	1	W14×30	W14×30	W12×35	HSS6×6×3/8	n/a	2.25
	2	W14×30	W14×30	W18×35	HSS4-1/2×4-1/2×5/16	HSS4×4×1/4	1.25
	3	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS3-1/2×3-1/2×1/4	0.5
Permutation	1	W14×30	W14×30	W12×35	HSS6×6×3/8	n/a	2.25
	2	W14×30	W14×30	W18×35	HSS4-1/2×4-1/2×5/16	HSS4×4×1/4	1.25
	3	W14×22	W14×22	W18×35	HSS4×4×1/4	HSS3-1/2×3-1/2×1/4	0.5
3X-20-Dmin							
Basic	1	W14×30	W14×30	W18×35	HSS5×5×5/16	n/a	1.25
	2	W14×30	W14×30	W18×35	HSS4×4×1/4	HSS3×3×3/16	0.5
	3	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS2-1/4×2-1/4×3/16	0.25
Amplified	1	W14×30	W14×30	W12×35	HSS5×5×5/16	n/a	1.25
	2	W14×30	W14×30	W18×35	HSS4×4×1/4	HSS3×3×3/16	0.5
	3	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS2-1/4×2-1/4×3/16	0.25
Modal	1	W14×30	W14×30	W12×35	HSS5×5×5/16	n/a	1.25
	2	W14×30	W14×30	W18×35	HSS4×4×1/4	HSS3×3×3/16	0.5
	3	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS2-1/2×2-1/2×3/16	0.25
Permutation	1	W14×30	W14×30	W12×35	HSS5×5×5/16	n/a	1.25
	2	W14×30	W14×30	W18×35	HSS4×4×1/4	HSS3-1/2×3-1/2×1/4	0.5
	3	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	0.25
3X-30-Dmax							
Basic	1	W14×43	W14×43	W12×45	HSS8×8×1/2	n/a	4.0
	2	W14×43	W14×43	W12×45	HSS6×6×3/8	HSS3-1/2×3-1/2×1/4	2.0
	3	W14×22	W14×22	W12×45	HSS5×5×5/16	HSS3×3×3/16	0.75
Amplified	1	W14×43	W14×43	W12×45	HSS8×8×1/2	n/a	4.0
	2	W14×43	W14×43	W12×45	HSS6×6×1/2	HSS3-1/2×3-1/2×1/4	2.0
	3	W14×22	W14×22	W12×45	HSS5-1/2×5-1/2×5/16	HSS3×3×3/16	0.75
Modal	1	W14×43	W14×43	W12×45	HSS8×8×1/2	n/a	4.0
	2	W14×43	W14×43	W12×45	HSS6×6×3/8	HSS4×4×1/4	2.0
	3	W14×22	W14×22	W12×45	HSS5×5×5/16	HSS3-1/2×3-1/2×1/4	0.75
Permutation	1	W14×43	W14×43	W12×45	HSS8×8×1/2	n/a	4.0
	2	W14×43	W14×43	W12×45	HSS6×6×3/8	HSS4-1/2×4-1/2×5/16	2.0
	3	W14×22	W14×22	W12×45	HSS5×5×5/16	HSS4×4×1/4	0.75
3X-30-Dmin							
Basic	1	W14×34	W14×38	W12×45	HSS6×6×1/2	n/a	2.5
	2	W14×34	W14×38	W12×45	HSS5-1/2×5-1/2×5/16	HSS3-1/2×3-1/2×1/4	0.75
	3	W14×22	W14×22	W12×45	HSS4-1/2×4-1/2×5/16	HSS2-1/4×2-1/4×3/16	0.5
Amplified	1	W14×34	W14×38	W12×45	HSS7×7×1/2	n/a	2.5

Table A.1 (continued)

Archetype	**Story**	**Left Col.**	**Right Col.**	**Beam**	**Brace**	**Tie**	**BRB**
	2	W14×34	W14×38	W12×45	HSS5-1/2×5-1/2×5/16	HSS3-1/2×3-1/2×1/4	0.75
	3	W14×22	W14×22	W12×45	HSS4-1/2×4-1/2×5/16	HSS2-1/4×2-1/4×3/16	0.5
Modal	1	W14×34	W14×38	W12×45	HSS6×6×1/2	n/a	2.5
	2	W14×34	W14×38	W12×45	HSS5-1/2×5-1/2×5/16	HSS4×4×1/4	0.75
	3	W14×22	W14×22	W12×45	HSS4-1/2×4-1/2×5/16	HSS3×3×1/4	0.5
Permutation	1	W14×34	W14×38	W12×45	HSS6×6×1/2	n/a	2.5
	2	W14×34	W14×38	W12×45	HSS5-1/2×5-1/2×5/16	HSS4×4×1/4	0.75
	3	W14×22	W14×22	W12×45	HSS4-1/2×4-1/2×5/16	HSS3-1/2×3-1/2×1/4	0.5
3Xo-20-Dmax							
Basic	1	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×3/8	n/a	2.25
	2	W14×30	W14×30	W12×45	HSS4×4×1/4	HSS3×3×3/16	1.5
	3	W14×22	W14×22	W12×45	HSS3-1/2×3-1/2×1/4	HSS2-1/4×2-1/4×3/16	0.5
Amplified	1	W14×30	W14×30	W12×45	HSS6×6×3/8	n/a	2.25
	2	W14×30	W14×30	W12×45	HSS4×4×1/4	HSS3×3×3/16	1.5
	3	W14×22	W14×22	W12×45	HSS3-1/2×3-1/2×1/4	HSS2-1/4×2-1/4×3/16	0.5
Modal	1	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×3/8	n/a	2.25
	2	W14×30	W14×30	W12×45	HSS4×4×5/16	HSS3-1/2×3-1/2×1/4	1.5
	3	W14×22	W14×22	W12×45	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	0.5
Permutation	1	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×3/8	n/a	2.25
	2	W14×30	W14×30	W12×45	HSS4×4×5/16	HSS3-1/2×3-1/2×1/4	1.5
	3	W14×22	W14×22	W12×45	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	0.5
3Xo-20-Dmax-Tall							
Basic	1	W14×43	W14×43	W12×45	HSS6×6×1/2	n/a	2.5
	2	W14×43	W14×43	W12×45	HSS4×4×5/16	HSS3×3×3/16	1.5
	3	W14×22	W14×22	W12×45	HSS3-1/2×3-1/2×1/4	HSS2-1/4×2-1/4×3/16	0.5
Amplified	1	W14×43	W14×43	W12×45	HSS7×7×1/2	n/a	2.5
	2	W14×43	W14×43	W12×45	HSS4×4×5/16	HSS3×3×3/16	1.5
	3	W14×22	W14×22	W12×45	HSS3-1/2×3-1/2×1/4	HSS2-1/4×2-1/4×3/16	0.5
Modal	1	W14×43	W14×43	W12×45	HSS6×6×1/2	n/a	2.5
	2	W14×43	W14×43	W12×45	HSS4×4×5/16	HSS3×3×3/16	1.5
	3	W14×22	W14×22	W12×45	HSS3-1/2×3-1/2×1/4	HSS2-1/2×2-1/2×3/16	0.5
Permutation	1	W14×43	W14×43	W12×45	HSS6×6×1/2	n/a	2.5
	2	W14×43	W14×43	W12×45	HSS4×4×5/16	HSS3-1/2×3-1/2×1/4	1.5
	3	W14×22	W14×22	W12×45	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	0.5
3Xo-20-Dmin							
Basic	1	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	n/a	1.25
	2	W14×30	W14×30	W12×45	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	0.75
	3	W14×22	W14×22	W12×45	HSS3×3×3/16	HSS2-1/4×2-1/4×3/16	0.25
Amplified	1	W14×30	W14×30	W12×45	HSS5×5×5/16	n/a	1.25
	2	W14×30	W14×30	W12×45	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	0.75
	3	W14×22	W14×22	W12×45	HSS3×3×3/16	HSS2-1/4×2-1/4×3/16	0.25
Modal	1	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	n/a	1.25
	2	W14×30	W14×30	W12×45	HSS3-1/2×3-1/2×1/4	HSS3×3×1/4	0.75
	3	W14×22	W14×22	W12×45	HSS3×3×3/16	HSS2-1/2×2-1/2×3/16	0.25

Table A.1 (continued)

Archetype	**Story**	**Left Col.**	**Right Col.**	**Beam**	**Brace**	**Tie**	**BRB**
Permutation	1	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	n/a	1.25
	2	W14×30	W14×30	W12×45	HSS3-1/2×3-1/2×1/4	HSS3×3×1/4	0.75
	3	W14×22	W14×22	W12×45	HSS3×3×3/16	HSS2-1/2×2-1/2×3/16	0.25
3Xo-30-Dmax							
Basic	1	W14×43	W14×43	W14×68	HSS7×7×1/2	n/a	4.25
	2	W14×43	W14×43	W14×68	HSS5×5×5/16	HSS3-1/2×3-1/2×1/4	2.5
	3	W14×22	W14×22	W14×68	HSS4×4×5/16	HSS2-1/4×2-1/4×3/16	1.0
Amplified	1	W14×43	W14×43	W14×68	HSS7×7×1/2	n/a	4.25
	2	W14×43	W14×43	W14×68	HSS5-1/2×5-1/2×5/16	HSS3-1/2×3-1/2×1/4	2.5
	3	W14×22	W14×22	W14×68	HSS4-1/2×4-1/2×5/16	HSS2-1/4×2-1/4×3/16	1.0
Modal	1	W14×43	W14×43	W14×68	HSS7×7×1/2	n/a	4.25
	2	W14×43	W14×43	W14×68	HSS5×5×5/16	HSS4×4×1/4	2.5
	3	W14×22	W14×22	W14×68	HSS4×4×5/16	HSS3-1/2×3-1/2×1/4	1.0
Permutation	1	W14×43	W14×43	W14×68	HSS7×7×1/2	n/a	4.25
	2	W14×43	W14×43	W14×68	HSS5×5×5/16	HSS4×4×1/4	2.5
	3	W14×22	W14×22	W14×68	HSS4×4×5/16	HSS3-1/2×3-1/2×1/4	1.0
3Xo-30-Dmax-Tall							
Basic	1	W14×53	W14×48	W14×68	HSS8×8×1/2	n/a	4.5
	2	W14×53	W14×48	W14×68	HSS5-1/2×5-1/2×5/16	HSS3-1/2×3-1/2×1/4	2.5
	3	W14×22	W14×22	W14×68	HSS4×4×5/16	HSS2-1/4×2-1/4×3/16	1.0
Amplified	1	W14×61	W14×53	W14×68	HSS8×8×1/2	n/a	4.5
	2	W14×61	W14×53	W14×68	HSS5-1/2×5-1/2×5/16	HSS3-1/2×3-1/2×1/4	2.5
	3	W14×22	W14×22	W14×68	HSS4×4×5/16	HSS2-1/4×2-1/4×3/16	1.0
Modal	1	W14×53	W14×48	W14×68	HSS8×8×1/2	n/a	4.5
	2	W14×53	W14×48	W14×68	HSS5-1/2×5-1/2×5/16	HSS4×4×1/4	2.5
	3	W14×22	W14×22	W14×68	HSS4×4×1/4	HSS3-1/2×3-1/2×1/4	1.0
Permutation	1	W14×53	W14×48	W14×68	HSS8×8×1/2	n/a	4.5
	2	W14×53	W14×48	W14×68	HSS5-1/2×5-1/2×5/16	HSS4×4×1/4	2.5
	3	W14×22	W14×22	W14×68	HSS4×4×1/4	HSS3-1/2×3-1/2×1/4	1.0
3Xo-30-Dmin							
Basic	1	W14×34	W14×34	W14×68	HSS5-1/2×5-1/2×3/8	n/a	2.5
	2	W14×34	W14×34	W14×68	HSS4-1/2×4-1/2×5/16	HSS3×3×5/16	1.0
	3	W14×22	W14×22	W14×68	HSS3-1/2×3-1/2×1/4	HSS2-1/4×2-1/4×3/16	0.5
Amplified	1	W14×34	W14×34	W14×68	HSS6×6×3/8	n/a	2.5
	2	W14×34	W14×34	W14×68	HSS4-1/2×4-1/2×5/16	HSS3-1/2×3-1/2×1/4	1.0
	3	W14×22	W14×22	W14×68	HSS4×4×1/4	HSS2-1/4×2-1/4×3/16	0.5
Modal	1	W14×34	W14×34	W14×68	HSS5-1/2×5-1/2×3/8	n/a	2.5
	2	W14×34	W14×34	W14×68	HSS4-1/2×4-1/2×5/16	HSS3-1/2×3-1/2×1/4	1.0
	3	W14×22	W14×22	W14×68	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	0.5
Permutation	1	W14×34	W14×34	W14×68	HSS5-1/2×5-1/2×3/8	n/a	2.5
	2	W14×34	W14×34	W14×68	HSS4-1/2×4-1/2×5/16	HSS3-1/2×3-1/2×1/4	1.0
	3	W14×22	W14×22	W14×68	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	0.5
4C-20-Dmax							
Basic	1	W14×43	W14×43	W12×35	HSS6×6×1/2	n/a	2.75

Table A.1 (continued)

Archetype	**Story**	**Left Col.**	**Right Col.**	**Beam**	**Brace**	**Tie**	**BRB**
	2	W14×43	W14×43	W12×35	HSS5-$^1/_2$×5-$^1/_2$×$^5/_{16}$	HSS3×3×$^3/_{16}$	2.0
	3	W14×22	W14×26	W12×35	HSS4-$^1/_2$×4-$^1/_2$×$^3/_8$	HSS2-$^1/_2$×2-$^1/_2$×$^1/_4$	1.25
	4	W14×22	W14×26	W18×35	HSS3-$^1/_2$×3-$^1/_2$×$^1/_4$	HSS2-$^1/_2$×2-$^1/_2$×$^3/_{16}$	0.5
Amplified	1	W14×43	W14×43	W12×35	HSS6×6×$^1/_2$	n/a	2.75
	2	W14×43	W14×43	W12×35	HSS5-$^1/_2$×5-$^1/_2$×$^5/_{16}$	HSS3×3×$^3/_{16}$	2.0
	3	W14×22	W14×26	W12×35	HSS5×5×$^5/_{16}$	HSS3×3×$^3/_{16}$	1.25
	4	W14×22	W14×26	W18×35	HSS4×4×$^1/_4$	HSS2-$^1/_2$×2-$^1/_2$×$^3/_{16}$	0.5
Modal	1	W14×43	W14×43	W12×35	HSS6×6×$^1/_2$	n/a	2.75
	2	W14×43	W14×43	W12×35	HSS5-$^1/_2$×5-$^1/_2$×$^5/_{16}$	HSS5×5×$^5/_{16}$	2.0
	3	W14×26	W14×26	W12×35	HSS4-$^1/_2$×4-$^1/_2$×$^5/_{16}$	HSS4-$^1/_2$×4-$^1/_2$×$^5/_{16}$	1.25
	4	W14×26	W14×26	W18×35	HSS3-$^1/_2$×3-$^1/_2$×$^1/_4$	HSS3-$^1/_2$×3-$^1/_2$×$^1/_4$	0.5
Permutation	1	W14×43	W14×43	W12×35	HSS6×6×$^1/_2$	n/a	2.75
	2	W14×43	W14×43	W12×35	HSS5-$^1/_2$×5-$^1/_2$×$^5/_{16}$	HSS5-$^1/_2$×5-$^1/_2$×$^5/_{16}$	2.0
	3	W14×26	W14×26	W12×35	HSS4-$^1/_2$×4-$^1/_2$×$^5/_{16}$	HSS4-$^1/_2$×4-$^1/_2$×$^5/_{16}$	1.25
	4	W14×26	W14×26	W18×35	HSS3-$^1/_2$×3-$^1/_2$×$^1/_4$	HSS4×4×$^1/_4$	0.5
4C-20-Dmin							
Basic	1	W14×30	W14×34	W12×35	HSS5×5×$^5/_{16}$	n/a	1.25
	2	W14×30	W14×34	W12×35	HSS4-$^1/_2$×4-$^1/_2$×$^5/_{16}$	HSS2-$^1/_2$×2-$^1/_2$×$^1/_4$	1.0
	3	W14×22	W14×22	W18×35	HSS4×4×$^1/_4$	HSS3×3×$^3/_{16}$	0.5
	4	W14×22	W14×22	W18×35	HSS3×3×$^3/_{16}$	HSS2-$^1/_4$×2-$^1/_4$×$^3/_{16}$	0.25
Amplified	1	W14×34	W14×34	W12×35	HSS5-$^1/_2$×5-$^1/_2$×$^5/_{16}$	n/a	1.25
	2	W14×34	W14×34	W12×35	HSS4-$^1/_2$×4-$^1/_2$×$^5/_{16}$	HSS3×3×$^3/_{16}$	1.0
	3	W14×22	W14×22	W18×35	HSS4×4×$^1/_4$	HSS3×3×$^3/_{16}$	0.5
	4	W14×22	W14×22	W18×35	HSS3×3×$^3/_{16}$	HSS2-$^1/_4$×2-$^1/_4$×$^3/_{16}$	0.25
Modal	1	W14×30	W14×34	W12×35	HSS5-$^1/_2$×5-$^1/_2$×$^5/_{16}$	n/a	1.25
	2	W14×30	W14×34	W12×35	HSS4-$^1/_2$×4-$^1/_2$×$^5/_{16}$	HSS4×4×$^1/_4$	1.0
	3	W14×22	W14×22	W18×35	HSS4×4×$^1/_4$	HSS4×4×$^1/_4$	0.5
	4	W14×22	W14×22	W18×35	HSS3×3×$^3/_{16}$	HSS3×3×$^3/_{16}$	0.25
Permutation	1	W14×34	W14×34	W12×35	HSS5-$^1/_2$×5-$^1/_2$×$^5/_{16}$	n/a	1.25
	2	W14×34	W14×34	W12×35	HSS4-$^1/_2$×4-$^1/_2$×$^5/_{16}$	HSS4×4×$^5/_{16}$	1.0
	3	W14×22	W14×22	W18×35	HSS4×4×$^1/_4$	HSS4×4×$^1/_4$	0.5
	4	W14×22	W14×22	W18×35	HSS3×3×$^3/_{16}$	HSS3×3×$^1/_4$	0.25
4C-30-Dmax							
Basic	1	W14×61	W14×61	W12×45	HSS8×8×$^1/_2$	n/a	5.0
	2	W14×61	W14×61	W12×45	HSS7×7×$^1/_2$	HSS3-$^1/_2$×3-$^1/_2$×$^1/_4$	3.5
	3	W14×30	W14×30	W12×45	HSS6×6×$^1/_2$	HSS3-$^1/_2$×3-$^1/_2$×$^1/_4$	2.25
	4	W14×30	W14×30	W12×45	HSS5×5×$^5/_{16}$	HSS3×3×$^1/_4$	0.75
Amplified	1	W14×61	W14×61	W12×45	HSS8×8×$^1/_2$	n/a	5.0
	2	W14×61	W14×61	W12×45	HSS7×7×$^1/_2$	HSS3-$^1/_2$×3-$^1/_2$×$^1/_4$	3.5
	3	W14×30	W14×30	W12×45	HSS6×6×$^1/_2$	HSS3-$^1/_2$×3-$^1/_2$×$^1/_4$	2.25
	4	W14×30	W14×30	W12×45	HSS5-$^1/_2$×5-$^1/_2$×$^5/_{16}$	HSS3-$^1/_2$×3-$^1/_2$×$^1/_4$	0.75
Modal	1	W14×61	W14×61	W12×45	HSS8×8×$^1/_2$	n/a	5.5
	2	W14×61	W14×61	W12×45	HSS7×7×$^1/_2$	HSS6×6×$^1/_2$	3.5
	3	W14×30	W14×30	W12×45	HSS6×6×$^1/_2$	HSS6×6×$^3/_8$	2.25
	4	W14×30	W14×30	W12×45	HSS5×5×$^5/_{16}$	HSS4×4×$^1/_4$	0.75

Table A.1 (continued)

Archetype	Story	Left Col.	Right Col.	Beam	Brace	Tie	BRB
Permutation	1	W14×61	W14×61	W12×45	HSS8×8×1/2	n/a	5.5
	2	W14×61	W14×61	W12×45	HSS7×7×1/2	HSS6×6×1/2	3.5
	3	W14×30	W14×30	W12×45	HSS6×6×3/8	HSS6×6×3/8	2.25
	4	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	HSS4-1/2×4-1/2×5/16	0.75
4C-30-Dmin							
Basic	1	W14×43	W14×48	W12×45	HSS7×7×1/2	n/a	2.5
	2	W14×43	W14×48	W12×45	HSS6×6×3/8	HSS3-1/2×3-1/2×1/4	1.5
	3	W14×30	W14×30	W12×45	HSS5×5×5/16	HSS3×3×3/16	1.0
	4	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	HSS2-1/2×2-1/2×3/16	0.5
Amplified	1	W14×43	W14×48	W12×45	HSS7×7×1/2	n/a	2.5
	2	W14×43	W14×48	W12×45	HSS6×6×3/8	HSS3-1/2×3-1/2×1/4	1.5
	3	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	HSS3×3×1/4	1.0
	4	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	HSS2-1/2×2-1/2×3/16	0.5
Modal	1	W14×43	W14×48	W12×45	HSS7×7×1/2	n/a	2.5
	2	W14×43	W14×48	W12×45	HSS6×6×3/8	HSS5×5×5/16	1.5
	3	W14×30	W14×30	W12×45	HSS5×5×5/16	HSS4-1/2×4-1/2×5/16	1.0
	4	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	HSS3-1/2×3-1/2×1/4	0.5
Permutation	1	W14×43	W14×48	W12×45	HSS7×7×1/2	n/a	2.5
	2	W14×43	W14×48	W12×45	HSS6×6×3/8	HSS5×5×5/16	1.5
	3	W14×30	W14×30	W12×45	HSS5×5×5/16	HSS4-1/2×4-1/2×5/16	1.0
	4	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	HSS3-1/2×3-1/2×1/4	0.5
4X-20-Dmax							
Basic	1	W14×43	W14×43	W12×35	HSS7×7×1/2	n/a	3.25
	2	W14×43	W14×43	W18×35	HSS5×5×5/16	HSS3×3×3/16	2.25
	3	W14×22	W14×26	W12×35	HSS5×5×5/16	HSS3×3×3/16	1.5
	4	W14×22	W14×26	W18×35	HSS4×4×1/4	n/a	0.5
Amplified	1	W14×43	W14×43	W12×35	HSS7×7×1/2	n/a	3.25
	2	W14×43	W14×43	W18×35	HSS5-1/2×5-1/2×5/16	HSS3×3×3/16	2.25
	3	W14×22	W14×26	W12×35	HSS5×5×5/16	HSS3×3×3/16	1.5
	4	W14×22	W14×26	W18×35	HSS4×4×1/4	n/a	0.5
Modal	1	W14×43	W14×43	W12×35	HSS7×7×1/2	n/a	3.25
	2	W14×43	W14×43	W12×35	HSS5×5×5/16	HSS4-1/2×4-1/2×5/16	2.25
	3	W14×26	W14×26	W12×35	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	1.5
	4	W14×26	W14×26	W18×35	HSS4×4×1/4	n/a	0.5
Permutation	1	W14×43	W14×43	W12×35	HSS7×7×1/2	n/a	3.25
	2	W14×43	W14×43	W12×35	HSS5×5×5/16	HSS4-1/2×4-1/2×5/16	2.25
	3	W14×26	W14×26	W12×35	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	1.5
	4	W14×26	W14×26	W18×35	HSS4×4×1/4	n/a	0.5
4X-20-Dmin							
Basic	1	W14×30	W14×34	W18×35	HSS5-1/2×5-1/2×5/16	n/a	1.5
	2	W14×30	W14×34	W18×35	HSS4×4×5/16	HSS3×3×3/16	0.75
	3	W14×22	W14×22	W18×35	HSS4×4×1/4	HSS2-1/2×2-1/2×3/16	0.75
	4	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	n/a	0.25
Amplified	1	W14×34	W14×34	W12×35	HSS5-1/2×5-1/2×3/8	n/a	1.5
	2	W14×34	W14×34	W18×35	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	0.75

Table A.1 (continued)

Archetype	**Story**	**Left Col.**	**Right Col.**	**Beam**	**Brace**	**Tie**	**BRB**
	3	W14×22	W14×22	W18×35	HSS4×4×1/4	HSS2-1/2×2-1/2×3/16	0.75
	4	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	n/a	0.25
Modal	1	W14×30	W14×30	W12×35	HSS5-1/2×5-1/2×3/8	n/a	1.5
	2	W14×30	W14×30	W18×35	HSS4×4×5/16	HSS4×4×1/4	0.75
	3	W14×22	W14×22	W18×35	HSS4×4×1/4	HSS3-1/2×3-1/2×1/4	0.75
	4	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	n/a	0.25
Permutation	1	W14×34	W14×34	W12×35	HSS5-1/2×5-1/2×3/8	n/a	1.75
	2	W14×34	W14×34	W18×35	HSS4×4×5/16	HSS4×4×1/4	0.75
	3	W14×22	W14×22	W12×35	HSS4×4×1/4	HSS3-1/2×3-1/2×1/4	0.75
	4	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	n/a	0.25
4X-30-Dmax							
Basic	1	W14×61	W14×61	W12×45	HSS8×8×5/8	n/a	5.5
	2	W14×61	W14×61	W12×45	HSS7×7×1/2	HSS3-1/2×3-1/2×1/4	3.5
	3	W14×30	W14×30	W12×45	HSS6×6×1/2	HSS2-1/2×2-1/2×3/16	2.5
	4	W14×30	W14×30	W12×45	HSS5×5×5/16	n/a	0.75
Amplified	1	W14×61	W14×61	W12×45	HSS9×9×5/8	n/a	5.5
	2	W14×61	W14×61	W12×45	HSS7×7×1/2	HSS3-1/2×3-1/2×1/4	3.5
	3	W14×30	W14×30	W12×45	HSS6×6×1/2	HSS2-1/2×2-1/2×3/16	2.5
	4	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	0.75
Modal	1	W14×61	W14×61	W12×45	HSS8×8×5/8	n/a	6.0
	2	W14×61	W14×61	W12×45	HSS7×7×1/2	HSS5-1/2×5-1/2×3/8	3.5
	3	W14×30	W14×30	W12×45	HSS6×6×1/2	HSS5-1/2×5-1/2×5/16	2.5
	4	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	0.75
Permutation	1	W14×61	W14×68	W12×45	HSS8×8×5/8	n/a	6.0
	2	W14×61	W14×68	W12×45	HSS7×7×1/2	HSS5-1/2×5-1/2×3/8	3.5
	3	W14×30	W14×30	W12×45	HSS6×6×5/8	HSS5-1/2×5-1/2×5/16	2.5
	4	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	0.75
4X-30-Dmin							
Basic	1	W14×43	W14×48	W12×45	HSS7×7×1/2	n/a	3.0
	2	W14×43	W14×48	W12×45	HSS5-1/2×5-1/2×3/8	HSS3-1/2×3-1/2×1/4	1.0
	3	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	HSS2-1/2×2-1/2×3/16	1.0
	4	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	n/a	0.5
Amplified	1	W14×43	W14×48	W12×45	HSS7×7×1/2	n/a	3.0
	2	W14×43	W14×48	W12×45	HSS5-1/2×5-1/2×3/8	HSS3-1/2×3-1/2×1/4	1.0
	3	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	HSS2-1/2×2-1/2×3/16	1.0
	4	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	n/a	0.5
Modal	1	W14×43	W14×48	W12×45	HSS7×7×1/2	n/a	3.0
	2	W14×43	W14×48	W12×45	HSS5-1/2×5-1/2×5/16	HSS4-1/2×4-1/2×5/16	1.0
	3	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	HSS4×4×5/16	1.0
	4	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	n/a	0.5
Permutation	1	W14×43	W14×48	W12×45	HSS7×7×1/2	n/a	3.0
	2	W14×43	W14×48	W12×45	HSS5-1/2×5-1/2×5/16	HSS4-1/2×4-1/2×5/16	1.0
	3	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	HSS4×4×5/16	1.0
	4	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	n/a	0.5

Table A.1 (continued)

Archetype	Story	Left Col.	Right Col.	Beam	Brace	Tie	BRB
4Xo-20-Dmax							
Basic	1	W14×43	W14×43	W12×45	HSS6×6×5/8	n/a	3.0
	2	W14×43	W14×43	W12×45	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	2.75
	3	W14×22	W14×26	W12×45	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	1.75
	4	W14×22	W14×26	W12×45	HSS3-1/2×3-1/2×1/4	n/a	0.5
Amplified	1	W14×48	W14×43	W12×45	HSS7×7×1/2	n/a	3.0
	2	W14×48	W14×43	W12×45	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	2.75
	3	W14×22	W14×26	W12×45	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	1.75
	4	W14×22	W14×26	W12×45	HSS4×4×1/4	n/a	0.5
Modal	1	W14×43	W14×38	W12×45	HSS7×7×1/2	n/a	3.0
	2	W14×43	W14×38	W12×45	HSS4-1/2×4-1/2×5/16	HSS4×4×5/16	2.75
	3	W14×26	W14×26	W12×45	HSS4×4×5/16	HSS4×4×1/4	1.75
	4	W14×26	W14×26	W12×45	HSS4×4×1/4	n/a	0.5
Permutation	1	W14×43	W14×38	W12×45	HSS7×7×1/2	n/a	3.0
	2	W14×43	W14×38	W12×45	HSS4-1/2×4-1/2×5/16	HSS4×4×5/16	2.75
	3	W14×26	W14×26	W12×45	HSS4×4×5/16	HSS4×4×1/4	1.75
	4	W14×26	W14×26	W12×45	HSS4×4×1/4	n/a	0.5
4Xo-20-Dmin							
Basic	1	W14×34	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	1.5
	2	W14×34	W14×30	W12×45	HSS4×4×1/4	HSS3×3×3/16	1.0
	3	W14×22	W14×22	W12×45	HSS4×4×1/4	HSS2-1/4×2-1/4×3/16	0.75
	4	W14×22	W14×22	W12×45	HSS3×3×3/16	n/a	0.25
Amplified	1	W14×34	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	1.5
	2	W14×34	W14×30	W12×45	HSS4×4×1/4	HSS3×3×3/16	1.0
	3	W14×22	W14×22	W12×45	HSS4×4×1/4	HSS2-1/2×2-1/2×3/16	0.75
	4	W14×22	W14×22	W12×45	HSS3×3×3/16	n/a	0.25
Modal	1	W14×34	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	1.5
	2	W14×34	W14×30	W12×45	HSS4×4×1/4	HSS4×4×1/4	1.0
	3	W14×22	W14×22	W12×45	HSS3-1/2×3-1/2×1/4	HSS3-1/2×3-1/2×1/4	0.75
	4	W14×22	W14×22	W12×45	HSS3×3×3/16	n/a	0.25
Permutation	1	W14×34	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	1.5
	2	W14×34	W14×30	W12×45	HSS4×4×1/4	HSS4×4×1/4	1.0
	3	W14×22	W14×22	W12×45	HSS3-1/2×3-1/2×1/4	HSS3-1/2×3-1/2×1/4	0.75
	4	W14×22	W14×22	W12×45	HSS3×3×3/16	n/a	0.25
4Xo-30-Dmax							
Basic	1	W14×61	W14×61	W14×68	HSS8×8×1/2	n/a	5.5
	2	W14×61	W14×61	W14×68	HSS5-1/2×5-1/2×3/8	HSS3-1/2×3-1/2×1/4	4.25
	3	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×5/16	HSS3×3×3/16	3.0
	4	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	1.0
Amplified	1	W14×61	W14×61	W14×68	HSS8×8×1/2	n/a	5.5
	2	W14×61	W14×61	W14×68	HSS5-1/2×5-1/2×3/8	HSS3-1/2×3-1/2×1/4	4.25
	3	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×5/16	HSS3×3×3/16	3.0
	4	W14×30	W14×30	W14×68	HSS5×5×5/16	n/a	1.0
Modal	1	W14×61	W14×61	W14×68	HSS8×8×1/2	n/a	5.5
	2	W14×61	W14×61	W14×68	HSS5-1/2×5-1/2×3/8	HSS5-1/2×5-1/2×5/16	4.25

Table A.1 (continued)

Archetype	**Story**	**Left Col.**	**Right Col.**	**Beam**	**Brace**	**Tie**	**BRB**
	3	W14×30	W14×30	W14×68	HSS5×5×5/16	HSS5×5×5/16	3.0
	4	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	1.0
Permutation	1	W14×61	W14×61	W14×68	HSS8×8×1/2	n/a	5.5
	2	W14×61	W14×61	W14×68	HSS5-1/2×5-1/2×3/8	HSS5-1/2×5-1/2×5/16	4.25
	3	W14×30	W14×30	W14×68	HSS5×5×5/16	HSS5×5×5/16	3.0
	4	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	1.0
4Xo-30-Dmax-Heavy							
Basic	1	W14×74	W14×61	W14×68	HSS9×9×5/8	n/a	7.5
	2	W14×74	W14×61	W14×68	HSS6×6×3/8	HSS4×4×5/16	6.5
	3	W14×30	W14×34	W14×68	HSS5-1/2×5-1/2×5/16	HSS3-1/2×3-1/2×1/4	4.25
	4	W14×30	W14×34	W14×68	HSS5×5×5/16	n/a	0.75
Amplified	1	W14×74	W14×68	W14×68	HSS9×9×5/8	n/a	7.5
	2	W14×74	W14×68	W14×68	HSS6×6×1/2	HSS4×4×1/4	6.5
	3	W14×30	W14×34	W14×68	HSS5-1/2×5-1/2×3/8	HSS3-1/2×3-1/2×1/4	4.25
	4	W14×30	W14×34	W14×68	HSS5×5×5/16	n/a	0.75
Modal	1	W14×74	W14×61	W14×82	HSS9×9×5/8	n/a	8.0
	2	W14×74	W14×61	W14×68	HSS6×6×1/2	HSS5-1/2×5-1/2×3/8	6.5
	3	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×5/16	HSS5-1/2×5-1/2×5/16	4.25
	4	W14×30	W14×30	W14×68	HSS5×5×5/16	n/a	0.75
Permutation	1	W14×74	W14×68	W14×82	HSS9×9×5/8	n/a	7.5
	2	W14×74	W14×68	W14×68	HSS6×6×3/8	HSS5-1/2×5-1/2×3/8	7.0
	3	W14×30	W14×30	W14×68	HSS5-1/2×5-1/2×5/16	HSS5-1/2×5-1/2×5/16	4.25
	4	W14×30	W14×30	W14×68	HSS5×5×5/16	n/a	0.75
4Xo-30-Dmin							
Basic	1	W14×43	W14×43	W14×68	HSS6×6×1/2	n/a	2.75
	2	W14×43	W14×43	W14×68	HSS4-1/2×4-1/2×5/16	HSS3-1/2×3-1/2×1/4	1.5
	3	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	1.25
	4	W14×30	W14×30	W14×68	HSS3-1/2×3-1/2×1/4	n/a	0.5
Amplified	1	W14×43	W14×43	W14×68	HSS6×6×1/2	n/a	2.75
	2	W14×43	W14×43	W14×68	HSS5×5×5/16	HSS3-1/2×3-1/2×1/4	1.5
	3	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	1.25
	4	W14×30	W14×30	W14×68	HSS4×4×1/4	n/a	0.5
Modal	1	W14×43	W14×43	W14×68	HSS6×6×1/2	n/a	3.0
	2	W14×43	W14×43	W14×68	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	1.5
	3	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	HSS4×4×1/4	1.25
	4	W14×30	W14×30	W14×68	HSS4×4×1/4	n/a	0.5
Permutation	1	W14×43	W14×43	W14×68	HSS6×6×1/2	n/a	3.0
	2	W14×43	W14×43	W14×68	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	1.5
	3	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	HSS4×4×1/4	1.25
	4	W14×30	W14×30	W14×68	HSS4×4×1/4	n/a	0.5
6C-20-Dmax							
Basic	1	W14×68	W14×68	W12×35	HSS7×7×1/2	n/a	3.5
	2	W14×68	W14×68	W12×35	HSS6×6×3/8	HSS4×4×1/4	3.0
	3	W14×43	W14×43	W12×35	HSS5-1/2×5-1/2×3/8	HSS4×4×1/4	2.5
	4	W14×43	W14×43	W12×35	HSS5×5×5/16	HSS3-1/2×3-1/2×1/4	2.0

Table A.1 (continued)

Archetype	**Story**	**Left Col.**	**Right Col.**	**Beam**	**Brace**	**Tie**	**BRB**
	5	W14×22	W14×26	W12×35	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	1.25
	6	W14×22	W14×26	W18×35	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	0.5
Amplified	1	W14×74	W14×68	W12×35	HSS7×7×1/2	n/a	3.5
	2	W14×74	W14×68	W12×35	HSS6×6×1/2	HSS4×4×1/4	3.0
	3	W14×43	W14×43	W12×35	HSS5-1/2×5-1/2×3/8	HSS4×4×1/4	2.5
	4	W14×43	W14×43	W12×35	HSS5×5×5/16	HSS3-1/2×3-1/2×1/4	2.0
	5	W14×22	W14×26	W12×35	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	1.25
	6	W14×22	W14×26	W18×35	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	0.5
Modal	1	W14×68	W14×61	W12×35	HSS7×7×1/2	n/a	3.5
	2	W14×68	W14×61	W12×35	HSS6×6×1/2	HSS5-1/2×5-1/2×3/8	3.0
	3	W14×43	W14×38	W12×35	HSS5-1/2×5-1/2×5/16	HSS5-1/2×5-1/2×3/8	2.5
	4	W14×43	W14×38	W12×35	HSS4-1/2×4-1/2×5/16	HSS5-1/2×5-1/2×3/8	2.0
	5	W14×26	W14×26	W12×35	HSS4×4×5/16	HSS4-1/2×4-1/2×5/16	1.25
	6	W14×26	W14×26	W18×35	HSS3-1/2×3-1/2×1/4	HSS3-1/2×3-1/2×1/4	0.5
Permutation	1	W14×68	W14×61	W12×35	HSS8×8×1/2	n/a	3.75
	2	W14×68	W14×61	W12×35	HSS6×6×3/8	HSS6×6×1/2	3.0
	3	W14×43	W14×38	W12×35	HSS5-1/2×5-1/2×5/16	HSS6×6×1/2	2.5
	4	W14×43	W14×38	W12×35	HSS4-1/2×4-1/2×5/16	HSS5-1/2×5-1/2×3/8	2.0
	5	W14×26	W14×26	W12×35	HSS4×4×5/16	HSS5×5×5/16	1.25
	6	W14×26	W14×26	W18×35	HSS3-1/2×3-1/2×1/4	HSS4×4×1/4	0.5
6C-20-Dmin							
Basic	1	W14×43	W14×43	W12×35	HSS5-1/2×5-1/2×3/8	n/a	1.5
	2	W14×43	W14×43	W12×35	HSS5×5×5/16	HSS3-1/2×3-1/2×1/4	1.25
	3	W14×30	W14×30	W12×35	HSS4-1/2×4-1/2×5/16	HSS3-1/2×3-1/2×1/4	1.0
	4	W14×30	W14×30	W18×35	HSS4×4×1/4	HSS3×3×1/4	0.75
	5	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS2-1/2×2-1/2×5/16	0.5
	6	W14×22	W14×22	W18×35	HSS3×3×3/16	HSS2-1/4×2-1/4×3/16	0.25
Amplified	1	W14×43	W14×48	W12×35	HSS5-1/2×5-1/2×3/8	n/a	1.5
	2	W14×43	W14×48	W12×35	HSS5×5×5/16	HSS3-1/2×3-1/2×1/4	1.25
	3	W14×30	W14×30	W12×35	HSS4-1/2×4-1/2×5/16	HSS3-1/2×3-1/2×1/4	1.0
	4	W14×30	W14×30	W18×35	HSS4×4×1/4	HSS3×3×1/4	0.75
	5	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	0.5
	6	W14×22	W14×22	W18×35	HSS3×3×3/16	HSS2-1/4×2-1/4×3/16	0.25
Modal	1	W14×43	W14×43	W12×35	HSS6×6×3/8	n/a	1.75
	2	W14×43	W14×43	W12×35	HSS5×5×5/16	HSS4-1/2×4-1/2×5/16	1.25
	3	W14×30	W14×30	W12×35	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	1.0
	4	W14×30	W14×30	W18×35	HSS3-1/2×3-1/2×1/4	HSS4-1/2×4-1/2×5/16	0.75
	5	W14×22	W14×22	W18×35	HSS3×3×1/4	HSS4×4×1/4	0.5
	6	W14×22	W14×22	W18×35	HSS3×3×3/16	HSS3×3×3/16	0.25
Permutation	1	W14×43	W14×43	W12×35	HSS6×6×3/8	n/a	1.75
	2	W14×43	W14×43	W12×35	HSS5×5×5/16	HSS5×5×5/16	1.25
	3	W14×30	W14×30	W12×35	HSS4-1/2×4-1/2×5/16	HSS5×5×5/16	1.0
	4	W14×30	W14×30	W18×35	HSS3-1/2×3-1/2×1/4	HSS4-1/2×4-1/2×5/16	0.75
	5	W14×22	W14×22	W18×35	HSS3×3×3/16	HSS4×4×1/4	0.5
	6	W14×22	W14×22	W18×35	HSS3×3×3/16	HSS3×3×1/4	0.25

Table A.1 (continued)

Archetype	Story	Left Col.	Right Col.	Beam	Brace	Tie	BRB
6C-30-Dmax							
Basic	1	W14×109	W14×109	W12×45	HSS9×9×5/8	n/a	6.5
	2	W14×109	W14×109	W12×45	HSS8×8×1/2	HSS3-1/2×3-1/2×1/4	5.0
	3	W14×61	W14×61	W12×45	HSS7×7×1/2	HSS4×4×1/4	4.5
	4	W14×61	W14×61	W12×45	HSS7×7×1/2	HSS3-1/2×3-1/2×1/4	3.25
	5	W14×30	W14×30	W12×45	HSS6×6×3/8	HSS3-1/2×3-1/2×1/4	2.25
	6	W14×30	W14×30	W12×45	HSS5×5×5/16	HSS3×3×1/4	0.75
Amplified	1	W14×109	W14×109	W12×50	HSS9×9×5/8	n/a	6.5
	2	W14×109	W14×109	W12×45	HSS8×8×5/8	HSS3-1/2×3-1/2×1/4	5.0
	3	W14×61	W14×61	W12×45	HSS8×8×1/2	HSS4×4×1/4	4.5
	4	W14×61	W14×61	W12×45	HSS7×7×1/2	HSS3-1/2×3-1/2×1/4	3.25
	5	W14×30	W14×30	W12×45	HSS6×6×3/8	HSS3-1/2×3-1/2×1/4	2.25
	6	W14×30	W14×30	W12×45	HSS5×5×5/16	HSS3×3×1/4	0.75
Modal	1	W14×109	W14×109	W12×50	HSS9×9×5/8	n/a	7.0
	2	W14×109	W14×109	W12×45	HSS8×8×5/8	HSS7×7×5/8	5.0
	3	W14×61	W14×61	W12×45	HSS7×7×1/2	HSS7×7×1/2	4.5
	4	W14×61	W14×61	W12×45	HSS6×6×1/2	HSS7×7×1/2	3.25
	5	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×3/8	HSS5-1/2×5-1/2×5/16	2.25
	6	W14×30	W14×30	W12×45	HSS5×5×5/16	HSS4×4×1/4	0.75
Permutation	1	W14×109	W14×109	W12×50	HSS9×9×5/8	n/a	7.0
	2	W14×109	W14×109	W12×45	HSS8×8×5/8	HSS8×8×1/2	5.0
	3	W14×61	W14×61	W12×45	HSS7×7×1/2	HSS8×8×1/2	4.5
	4	W14×61	W14×61	W12×45	HSS6×6×1/2	HSS7×7×1/2	3.25
	5	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×3/8	HSS6×6×3/8	2.0
	6	W14×30	W14×30	W12×45	HSS5×5×5/16	HSS4-1/2×4-1/2×5/16	0.75
6C-30-Dmin							
Basic	1	W14×61	W14×68	W12×45	HSS7×7×1/2	n/a	3.25
	2	W14×61	W14×68	W12×45	HSS6×6×1/2	HSS3-1/2×3-1/2×1/4	2.0
	3	W14×43	W14×43	W12×45	HSS6×6×3/8	HSS3-1/2×3-1/2×1/4	1.5
	4	W14×43	W14×43	W12×45	HSS5-1/2×5-1/2×5/16	HSS3-1/2×3-1/2×1/4	1.25
	5	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	HSS3-1/2×3-1/2×1/4	0.75
	6	W14×30	W14×30	W12×45	HSS4×4×1/4	HSS3×3×3/16	0.25
Amplified	1	W14×61	W14×68	W12×45	HSS8×8×1/2	n/a	3.25
	2	W14×61	W14×68	W12×45	HSS7×7×1/2	HSS3-1/2×3-1/2×1/4	2.0
	3	W14×43	W14×43	W12×45	HSS6×6×3/8	HSS3-1/2×3-1/2×1/4	1.5
	4	W14×43	W14×43	W12×45	HSS5-1/2×5-1/2×5/16	HSS3-1/2×3-1/2×1/4	1.25
	5	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	HSS3-1/2×3-1/2×1/4	0.75
	6	W14×30	W14×30	W12×45	HSS4×4×1/4	HSS3×3×3/16	0.25
Modal	1	W14×61	W14×68	W12×45	HSS7×7×1/2	n/a	3.5
	2	W14×61	W14×68	W12×45	HSS7×7×1/2	HSS5-1/2×5-1/2×5/16	2.0
	3	W14×43	W14×43	W12×45	HSS6×6×3/8	HSS5-1/2×5-1/2×5/16	1.5
	4	W14×43	W14×43	W12×45	HSS5×5×5/16	HSS5×5×5/16	1.25
	5	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	HSS4×4×1/4	0.75
	6	W14×30	W14×30	W12×45	HSS4×4×1/4	HSS3×3×1/4	0.25
Permutation	1	W14×61	W14×68	W12×45	HSS7×7×5/8	n/a	3.75
	2	W14×61	W14×68	W12×45	HSS7×7×1/2	HSS6×6×3/8	2.0

Table A.1 (continued)

Archetype	**Story**	**Left Col.**	**Right Col.**	**Beam**	**Brace**	**Tie**	**BRB**
	3	W14×43	W14×43	W12×45	HSS5-1/2×5-1/2×3/8	HSS6×6×3/8	1.5
	4	W14×43	W14×43	W12×45	HSS5×5×5/16	HSS5-1/2×5-1/2×5/16	1.25
	5	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	0.75
	6	W14×30	W14×30	W12×45	HSS4×4×1/4	HSS3-1/2×3-1/2×1/4	0.25
6X-20-Dmax							
Basic	1	W14×68	W14×68	W18×46	HSS8×8×5/8	n/a	4.25
	2	W14×68	W14×68	W18×46	HSS5-1/2×5-1/2×3/8	HSS4×4×1/4	3.25
	3	W14×43	W14×43	W18×46	HSS6×6×3/8	HSS4×4×5/16	3.0
	4	W14×43	W14×43	W18×35	HSS5×5×5/16	HSS3-1/2×3-1/2×1/4	2.25
	5	W14×22	W14×26	W18×40	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	1.25
	6	W14×22	W14×26	W18×35	HSS3-1/2×3-1/2×1/4	n/a	0.5
Amplified	1	W14×74	W14×68	W12×35	HSS8×8×5/8	n/a	4.25
	2	W14×74	W14×68	W12×35	HSS5-1/2×5-1/2×3/8	HSS4-1/2×4-1/2×5/16	3.0
	3	W14×43	W14×43	W12×35	HSS6×6×1/2	HSS4-1/2×4-1/2×5/16	3.0
	4	W14×43	W14×43	W18×35	HSS5×5×5/16	HSS3×3×1/4	2.25
	5	W14×22	W14×26	W12×35	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	1.25
	6	W14×22	W14×26	W18×35	HSS4×4×1/4	n/a	0.5
Modal	1	W14×68	W14×68	W12×35	HSS8×8×5/8	n/a	4.25
	2	W14×68	W14×68	W12×35	HSS5-1/2×5-1/2×5/16	HSS6×6×3/8	3.25
	3	W14×43	W14×43	W12×35	HSS6×6×3/8	HSS5-1/2×5-1/2×3/8	3.0
	4	W14×43	W14×43	W18×40	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	2.25
	5	W14×26	W14×26	W12×35	HSS4-1/2×4-1/2×5/16	HSS4×4×5/16	1.25
	6	W14×26	W14×26	W18×35	HSS4×4×1/4	n/a	0.5
Permutation	1	W14×74	W14×61	W12×45	HSS9×9×5/8	n/a	4.25
	2	W14×74	W14×61	W12×35	HSS5-1/2×5-1/2×5/16	HSS6×6×1/2	3.25
	3	W14×43	W14×38	W12×35	HSS6×6×3/8	HSS6×6×1/2	3.0
	4	W14×43	W14×38	W12×35	HSS5×5×5/16	HSS4-1/2×4-1/2×5/16	2.5
	5	W14×26	W14×26	W12×35	HSS4×4×5/16	HSS4-1/2×4-1/2×5/16	1.25
	6	W14×26	W14×26	W18×35	HSS4×4×1/4	n/a	0.5
6X-20-Dmin							
Basic	1	W14×43	W14×43	W18×46	HSS6×6×1/2	n/a	2.0
	2	W14×43	W14×43	W18×35	HSS4-1/2×4-1/2×5/16	HSS3-1/2×3-1/2×1/4	1.0
	3	W14×30	W14×30	W18×40	HSS5×5×5/16	HSS3-1/2×3-1/2×1/4	1.25
	4	W14×30	W14×30	W18×35	HSS4×4×1/4	HSS3×3×1/4	0.75
	5	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	0.5
	6	W14×22	W14×22	W18×35	HSS3×3×3/16	n/a	0.25
Amplified	1	W14×43	W14×43	W12×35	HSS6×6×5/8	n/a	2.25
	2	W14×43	W14×43	W18×35	HSS4-1/2×4-1/2×5/16	HSS4×4×1/4	1.0
	3	W14×30	W14×30	W12×35	HSS5×5×5/16	HSS4×4×1/4	1.25
	4	W14×30	W14×30	W18×35	HSS4×4×1/4	HSS3×3×1/4	0.75
	5	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	0.5
	6	W14×22	W14×22	W18×35	HSS3×3×3/16	n/a	0.25
Modal	1	W14×43	W14×43	W12×35	HSS6×6×1/2	n/a	2.25
	2	W14×43	W14×43	W18×40	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	1.0
	3	W14×30	W14×30	W12×35	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	1.25
	4	W14×30	W14×30	W18×35	HSS4×4×1/4	HSS4×4×1/4	0.75

Table A.1 (continued)

Archetype	Story	Left Col.	Right Col.	Beam	Brace	Tie	BRB
	5	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS3-1/2×3-1/2×1/4	0.5
	6	W14×22	W14×22	W18×35	HSS3×3×3/16	n/a	0.25
Permutation	1	W14×43	W14×43	W12×35	HSS6×6×5/8	n/a	2.25
	2	W14×43	W14×43	W12×35	HSS4-1/2×4-1/2×5/16	HSS5×5×5/16	1.0
	3	W14×30	W14×30	W12×35	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	1.25
	4	W14×30	W14×30	W18×35	HSS4×4×1/4	HSS4×4×1/4	0.75
	5	W14×22	W14×22	W18×35	HSS3-1/2×3-1/2×1/4	HSS3-1/2×3-1/2×1/4	0.5
	6	W14×22	W14×22	W18×35	HSS3×3×3/16	n/a	0.25
6X-30-Dmax							
Basic	1	W14×109	W14×109	W12×45	HSS10×10×5/8	n/a	7.5
	2	W14×109	W14×109	W12×45	HSS8×8×1/2	HSS4-1/2×4-1/2×5/16	4.5
	3	W14×61	W14×61	W12×45	HSS8×8×1/2	HSS4×4×5/16	4.75
	4	W14×61	W14×61	W12×45	HSS6×6×1/2	HSS3-1/2×3-1/2×1/4	3.5
	5	W14×30	W14×30	W12×45	HSS6×6×3/8	HSS3×3×3/16	2.25
	6	W14×30	W14×30	W12×45	HSS5×5×5/16	n/a	0.75
Amplified	1	W14×109	W14×109	W12×45	HSS10×10×5/8	n/a	7.5
	2	W14×109	W14×109	W12×45	HSS8×8×5/8	HSS4-1/2×4-1/2×5/16	4.5
	3	W14×61	W14×61	W12×45	HSS8×8×1/2	HSS4×4×3/8	5.0
	4	W14×61	W14×61	W12×45	HSS7×7×1/2	HSS3-1/2×3-1/2×1/4	3.5
	5	W14×30	W14×30	W12×45	HSS6×6×3/8	HSS3×3×1/4	2.5
	6	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	0.75
Modal	1	W14×109	W14×109	W12×45	HSS10×10×5/8	n/a	8.0
	2	W14×109	W14×109	W12×45	HSS8×8×1/2	HSS8×8×1/2	4.5
	3	W14×61	W14×61	W12×45	HSS8×8×1/2	HSS7×7×5/8	4.75
	4	W14×61	W14×61	W12×45	HSS6×6×1/2	HSS5-1/2×5-1/2×5/16	3.75
	5	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×3/8	HSS5×5×5/16	2.25
	6	W14×30	W14×30	W12×45	HSS5×5×5/16	n/a	0.75
Permutation	1	W14×109	W14×109	W14×68	HSS10×10×3/4	n/a	8.0
	2	W14×109	W14×109	W12×45	HSS8×8×1/2	HSS8×8×1/2	4.5
	3	W14×61	W14×61	W12×45	HSS8×8×1/2	HSS8×8×1/2	4.75
	4	W14×61	W14×61	W12×45	HSS6×6×1/2	HSS5-1/2×5-1/2×3/8	3.75
	5	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	HSS5-1/2×5-1/2×5/16	2.25
	6	W14×30	W14×30	W12×45	HSS5-1/2×5-1/2×5/16	n/a	0.75
6X-30-Dmin							
Basic	1	W14×61	W14×68	W12×45	HSS8×8×1/2	n/a	4.0
	2	W14×61	W14×68	W12×45	HSS6×6×3/8	HSS4×4×1/4	1.5
	3	W14×43	W14×43	W12×45	HSS6×6×1/2	HSS3-1/2×3-1/2×5/16	2.0
	4	W14×43	W14×43	W12×45	HSS5×5×5/16	HSS3-1/2×3-1/2×1/4	1.25
	5	W14×30	W14×30	W12×45	HSS5×5×5/16	HSS3×3×3/16	1.0
	6	W14×30	W14×30	W12×45	HSS4×4×5/16	n/a	0.25
Amplified	1	W14×61	W14×74	W12×45	HSS8×8×1/2	n/a	4.0
	2	W14×61	W14×74	W12×45	HSS6×6×1/2	HSS4×4×1/4	1.5
	3	W14×43	W14×43	W12×45	HSS6×6×1/2	HSS3-1/2×3-1/2×1/4	2.0
	4	W14×43	W14×43	W12×45	HSS5-1/2×5-1/2×5/16	HSS3-1/2×3-1/2×1/4	1.25
	5	W14×30	W14×30	W12×45	HSS5×5×5/16	HSS3×3×3/16	1.0
	6	W14×30	W14×30	W12×45	HSS4×4×5/16	n/a	0.25

Table A.1 (continued)

Archetype	Story	Left Col.	Right Col.	Beam	Brace	Tie	BRB
Modal	1	W14×61	W14×68	W12×45	HSS8×8×1/2	n/a	4.25
	2	W14×61	W14×68	W12×45	HSS6×6×3/8	HSS5-1/2×5-1/2×5/16	1.5
	3	W14×43	W14×43	W12×45	HSS6×6×1/2	HSS5×5×3/8	2.0
	4	W14×43	W14×43	W12×45	HSS5×5×5/16	HSS4×4×5/16	1.25
	5	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	HSS4×4×1/4	1.0
	6	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	n/a	0.25
Permutation	1	W14×61	W14×68	W12×45	HSS8×8×1/2	n/a	4.5
	2	W14×61	W14×68	W12×45	HSS6×6×1/2	HSS6×6×3/8	1.5
	3	W14×43	W14×43	W12×45	HSS6×6×3/8	HSS5-1/2×5-1/2×3/8	2.0
	4	W14×43	W14×43	W12×45	HSS5-1/2×5-1/2×5/16	HSS4-1/2×4-1/2×5/16	1.25
	5	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	HSS4×4×5/16	1.0
	6	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	n/a	0.25
6Xo-20-Dmax							
Basic	1	W14×74	W14×68	W12×45	HSS8×8×1/2	n/a	3.75
	2	W14×74	W14×68	W12×45	HSS4-1/2×4-1/2×5/16	HSS4×4×3/8	4.0
	3	W14×43	W14×43	W12×45	HSS6×6×3/8	HSS4×4×5/16	3.0
	4	W14×43	W14×43	W12×45	HSS4×4×5/16	HSS3×3×3/16	2.75
	5	W14×22	W14×26	W12×45	HSS4×4×5/16	HSS3×3×3/16	1.5
	6	W14×22	W14×26	W12×45	HSS3-1/2×3-1/2×1/4	n/a	0.5
Amplified	1	W14×82	W14×61	W12×45	HSS8×8×5/8	n/a	3.75
	2	W14×82	W14×61	W12×45	HSS4×4×5/16	HSS4-1/2×4-1/2×5/16	4.0
	3	W14×43	W14×43	W12×45	HSS6×6×3/8	HSS4-1/2×4-1/2×5/16	3.0
	4	W14×43	W14×43	W12×45	HSS4×4×5/16	HSS3×3×3/16	2.75
	5	W14×22	W14×26	W12×45	HSS4×4×5/16	HSS3×3×3/16	1.5
	6	W14×22	W14×26	W12×45	HSS3-1/2×3-1/2×1/4	n/a	0.5
Modal	1	W14×74	W14×61	W12×45	HSS8×8×5/8	n/a	3.75
	2	W14×74	W14×61	W12×45	HSS5×5×5/16	HSS5-1/2×5-1/2×3/8	4.0
	3	W14×43	W14×38	W12×45	HSS5-1/2×5-1/2×3/8	HSS5-1/2×5-1/2×3/8	3.0
	4	W14×43	W14×38	W12×45	HSS4-1/2×4-1/2×5/16	HSS4×4×5/16	2.75
	5	W14×26	W14×26	W12×45	HSS4×4×1/4	HSS4×4×1/4	1.5
	6	W14×26	W14×26	W12×45	HSS3-1/2×3-1/2×1/4	n/a	0.5
Permutation	1	W14×74	W14×61	W12×45	HSS8×8×5/8	n/a	3.75
	2	W14×74	W14×61	W12×45	HSS4-1/2×4-1/2×5/16	HSS6×6×3/8	4.0
	3	W14×43	W14×38	W12×45	HSS5-1/2×5-1/2×3/8	HSS6×6×3/8	3.0
	4	W14×43	W14×38	W12×45	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	2.75
	5	W14×26	W14×26	W12×45	HSS4×4×1/4	HSS4×4×1/4	1.5
	6	W14×26	W14×26	W12×45	HSS3-1/2×3-1/2×1/4	n/a	0.5
6Xo-20-Dmax-Tall							
Basic	1	W14×109	W14×68	W12×45	HSS9×9×5/8	n/a	4.25
	2	W14×109	W14×68	W12×45	HSS4×4×5/16	HSS4-1/2×4-1/2×5/16	3.75
	3	W14×43	W14×38	W12×45	HSS5-1/2×5-1/2×3/8	HSS4-1/2×4-1/2×5/16	3.0
	4	W14×43	W14×38	W12×45	HSS4×4×5/16	HSS3×3×3/16	2.5
	5	W14×22	W14×26	W12×45	HSS4×4×5/16	HSS3×3×3/16	1.5
	6	W14×22	W14×26	W12×45	HSS3-1/2×3-1/2×1/4	n/a	0.5
Amplified	1	W14×109	W14×68	W12×45	HSS9×9×5/8	n/a	4.25
	2	W14×109	W14×68	W12×45	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	3.75

Table A.1 (continued)

Archetype	**Story**	**Left Col.**	**Right Col.**	**Beam**	**Brace**	**Tie**	**BRB**
	3	W14×43	W14×43	W12×45	HSS6×6×3/8	HSS4-1/2×4-1/2×5/16	3.0
	4	W14×43	W14×43	W12×45	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	2.5
	5	W14×22	W14×26	W12×45	HSS4×4×5/16	HSS3×3×3/16	1.5
	6	W14×22	W14×26	W12×45	HSS3-1/2×3-1/2×1/4	n/a	0.5
Modal	1	W14×109	W14×68	W12×45	HSS9×9×5/8	n/a	4.25
	2	W14×109	W14×68	W12×45	HSS5×5×5/16	HSS5×5×5/16	3.75
	3	W14×43	W14×38	W12×45	HSS5-1/2×5-1/2×3/8	HSS5×5×5/16	3.0
	4	W14×43	W14×38	W12×45	HSS4-1/2×4-1/2×5/16	HSS4×4×5/16	2.5
	5	W14×26	W14×26	W12×45	HSS4×4×1/4	HSS4×4×1/4	1.5
	6	W14×26	W14×26	W12×45	HSS3-1/2×3-1/2×1/4	n/a	0.5
Permutation	1	W14×109	W14×61	W12×45	HSS9×9×5/8	n/a	4.25
	2	W14×109	W14×61	W12×45	HSS5×5×5/16	HSS6×6×3/8	3.75
	3	W14×43	W14×38	W12×45	HSS5-1/2×5-1/2×5/16	HSS6×6×3/8	3.0
	4	W14×43	W14×38	W12×45	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	2.5
	5	W14×26	W14×26	W12×45	HSS4×4×1/4	HSS4×4×1/4	1.5
	6	W14×26	W14×26	W12×45	HSS3-1/2×3-1/2×1/4	n/a	0.5
6Xo-20-Dmin							
Basic	1	W14×43	W14×43	W12×45	HSS6×6×3/8	n/a	1.75
	2	W14×43	W14×43	W12×45	HSS4×4×1/4	HSS3-1/2×3-1/2×1/4	1.25
	3	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	HSS3-1/2×3-1/2×1/4	1.25
	4	W14×30	W14×30	W12×45	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	1.0
	5	W14×22	W14×22	W12×45	HSS3-1/2×3-1/2×1/4	HSS2-1/2×2-1/2×3/16	0.5
	6	W14×22	W14×22	W12×45	HSS3×3×3/16	n/a	0.25
Amplified	1	W14×48	W14×43	W12×45	HSS6×6×1/2	n/a	1.75
	2	W14×48	W14×43	W12×45	HSS4×4×1/4	HSS4×4×1/4	1.25
	3	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	HSS4×4×1/4	1.25
	4	W14×30	W14×30	W12×45	HSS3-1/2×3-1/2×1/4	HSS3×3×3/16	1.0
	5	W14×22	W14×22	W12×45	HSS3-1/2×3-1/2×1/4	HSS2-1/2×2-1/2×3/16	0.5
	6	W14×22	W14×22	W12×45	HSS3×3×3/16	n/a	0.25
Modal	1	W14×43	W14×43	W12×45	HSS6×6×3/8	n/a	1.75
	2	W14×43	W14×43	W12×45	HSS4×4×1/4	HSS4×4×5/16	1.25
	3	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	HSS4×4×1/4	1.25
	4	W14×30	W14×30	W12×45	HSS3-1/2×3-1/2×1/4	HSS3-1/2×3-1/2×1/4	1.0
	5	W14×22	W14×22	W12×45	HSS3-1/2×3-1/2×1/4	HSS3×3×1/4	0.5
	6	W14×22	W14×22	W12×45	HSS3×3×3/16	n/a	0.25
Permutation	1	W14×43	W14×48	W12×45	HSS6×6×3/8	n/a	2.0
	2	W14×43	W14×48	W12×45	HSS4×4×1/4	HSS4-1/2×4-1/2×5/16	1.25
	3	W14×30	W14×30	W12×45	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	1.25
	4	W14×30	W14×30	W12×45	HSS4×4×1/4	HSS3-1/2×3-1/2×1/4	1.0
	5	W14×22	W14×22	W12×45	HSS3-1/2×3-1/2×1/4	HSS3-1/2×3-1/2×1/4	0.5
	6	W14×22	W14×22	W12×45	HSS3×3×3/16	n/a	0.25
6Xo-30-Dmax							
Basic	1	W14×109	W14×109	W14×68	HSS9×9×5/8	n/a	7.0
	2	W14×109	W14×109	W14×68	HSS6×6×3/8	HSS5×5×5/16	6.5
	3	W14×61	W14×61	W14×68	HSS7×7×1/2	HSS5×5×5/16	6.0
	4	W14×61	W14×61	W14×68	HSS5-1/2×5-1/2×3/8	HSS3-1/2×3-1/2×1/4	4.25

Table A.1 (continued)

Archetype	Story	Left Col.	Right Col.	Beam	Brace	Tie	BRB
	5	W14×30	W14×30	W14×68	HSS5×5×5/16	HSS3×3×3/16	2.75
	6	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
Amplified	1	W14×109	W14×109	W14×68	HSS10×10×5/8	n/a	7.0
	2	W14×109	W14×109	W14×68	HSS6×6×1/2	HSS5-1/2×5-1/2×5/16	6.5
	3	W14×61	W14×61	W14×68	HSS7×7×1/2	HSS5×5×5/16	6.0
	4	W14×61	W14×61	W14×68	HSS5-1/2×5-1/2×3/8	HSS3-1/2×3-1/2×1/4	4.25
	5	W14×30	W14×30	W14×68	HSS5×5×5/16	HSS3×3×1/4	2.75
	6	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
Modal	1	W14×109	W14×109	W14×68	HSS10×10×5/8	n/a	7.0
	2	W14×109	W14×109	W14×68	HSS6×6×3/8	HSS7×7×1/2	6.5
	3	W14×61	W14×53	W14×68	HSS7×7×1/2	HSS6×6×5/8	6.0
	4	W14×61	W14×53	W14×68	HSS5-1/2×5-1/2×3/8	HSS5×5×5/16	4.5
	5	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	2.75
	6	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
Permutation	1	W14×109	W14×109	W14×74	HSS10×10×5/8	n/a	7.0
	2	W14×109	W14×109	W14×68	HSS6×6×1/2	HSS7×7×1/2	6.5
	3	W14×61	W14×53	W14×68	HSS7×7×1/2	HSS7×7×1/2	6.0
	4	W14×61	W14×53	W14×68	HSS5-1/2×5-1/2×3/8	HSS5-1/2×5-1/2×5/16	4.75
	5	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	HSS5×5×5/16	2.75
	6	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
6Xo-30-Dmax-Tall							
Basic	1	W14×109	W14×109	W14×68	HSS10×10×3/4	n/a	7.5
	2	W14×109	W14×109	W14×68	HSS6×6×3/8	HSS5-1/2×5-1/2×5/16	6.5
	3	W14×61	W14×61	W14×68	HSS6×6×1/2	HSS5×5×5/16	5.5
	4	W14×61	W14×61	W14×68	HSS5-1/2×5-1/2×5/16	HSS3-1/2×3-1/2×1/4	4.0
	5	W14×30	W14×30	W14×68	HSS5×5×5/16	HSS3×3×3/16	2.5
	6	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
Amplified	1	W14×109	W14×109	W14×68	HSS10×10×3/4	n/a	7.5
	2	W14×109	W14×109	W14×68	HSS6×6×3/8	HSS5-1/2×5-1/2×5/16	6.5
	3	W14×61	W14×61	W14×68	HSS7×7×1/2	HSS5-1/2×5-1/2×5/16	5.5
	4	W14×61	W14×61	W14×68	HSS5-1/2×5-1/2×3/8	HSS3-1/2×3-1/2×1/4	4.0
	5	W14×30	W14×30	W14×68	HSS5×5×5/16	HSS3×3×1/4	2.5
	6	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
Modal	1	W14×109	W14×109	W14×68	HSS10×10×3/4	n/a	7.5
	2	W14×109	W14×109	W14×68	HSS6×6×3/8	HSS6×6×1/2	6.5
	3	W14×61	W14×48	W14×68	HSS6×6×1/2	HSS6×6×1/2	5.5
	4	W14×61	W14×48	W14×68	HSS5-1/2×5-1/2×5/16	HSS5×5×5/16	4.5
	5	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	2.5
	6	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75
Permutation	1	W14×109	W14×109	W14×74	HSS10×10×3/4	n/a	7.5
	2	W14×109	W14×109	W14×68	HSS6×6×1/2	HSS7×7×1/2	6.5
	3	W14×61	W14×48	W14×68	HSS6×6×1/2	HSS7×7×1/2	5.5
	4	W14×61	W14×48	W14×68	HSS5-1/2×5-1/2×5/16	HSS5-1/2×5-1/2×5/16	4.5
	5	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	HSS5×5×5/16	2.5
	6	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	n/a	0.75

Table A.1 (continued)

Archetype	Story	Left Col.	Right Col.	Beam	Brace	Tie	BRB
6Xo-30-Dmin							
Basic	1	W14×61	W14×61	W14×68	HSS7×7×1/2	n/a	3.75
	2	W14×61	W14×61	W14×68	HSS5×5×5/16	HSS4×4×5/16	2.0
	3	W14×43	W14×43	W14×68	HSS5-1/2×5-1/2×5/16	HSS4×4×1/4	2.25
	4	W14×43	W14×43	W14×68	HSS4-1/2×4-1/2×5/16	HSS3-1/2×3-1/2×1/4	1.5
	5	W14×30	W14×30	W14×68	HSS4×4×5/16	HSS3×3×3/16	1.0
	6	W14×30	W14×30	W14×68	HSS3-1/2×3-1/2×1/4	n/a	0.5
Amplified	1	W14×68	W14×61	W14×68	HSS7×7×5/8	n/a	3.75
	2	W14×68	W14×61	W14×68	HSS5×5×5/16	HSS4-1/2×4-1/2×5/16	2.0
	3	W14×43	W14×43	W14×68	HSS5-1/2×5-1/2×5/16	HSS4×4×5/16	2.25
	4	W14×43	W14×43	W14×68	HSS4-1/2×4-1/2×5/16	HSS3-1/2×3-1/2×1/4	1.5
	5	W14×30	W14×30	W14×68	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	1.0
	6	W14×30	W14×30	W14×68	HSS3-1/2×3-1/2×1/4	n/a	0.5
Modal	1	W14×61	W14×61	W14×68	HSS7×7×1/2	n/a	3.75
	2	W14×61	W14×61	W14×68	HSS5×5×5/16	HSS5×5×5/16	2.0
	3	W14×43	W14×43	W14×68	HSS5-1/2×5-1/2×5/16	HSS5×5×5/16	2.25
	4	W14×43	W14×43	W14×68	HSS4-1/2×4-1/2×5/16	HSS4×4×5/16	1.5
	5	W14×30	W14×30	W14×68	HSS4×4×1/4	HSS4×4×1/4	1.0
	6	W14×30	W14×30	W14×68	HSS3-1/2×3-1/2×1/4	n/a	0.5
Permutation	1	W14×61	W14×61	W14×68	HSS7×7×1/2	n/a	4.0
	2	W14×61	W14×61	W14×68	HSS5×5×5/16	HSS5-1/2×5-1/2×3/8	2.0
	3	W14×43	W14×43	W14×68	HSS5-1/2×5-1/2×5/16	HSS5-1/2×5-1/2×5/16	2.25
	4	W14×43	W14×43	W14×68	HSS4-1/2×4-1/2×5/16	HSS4-1/2×4-1/2×5/16	1.5
	5	W14×30	W14×30	W14×68	HSS4×4×1/4	HSS4×4×1/4	1.0
	6	W14×30	W14×30	W14×68	HSS3-1/2×3-1/2×1/4	n/a	0.5
9X-30-Dmax							
Basic	1	W14×176	W14×193	W12×45	HSS10×10×3/4	n/a	8.5
	2	W14×176	W14×193	W12×45	HSS8×8×5/8	HSS5-1/2×5-1/2×3/8	5.5
	3	W14×109	W14×120	W12×45	HSS9×9×5/8	HSS5-1/2×5-1/2×5/16	6.5
	4	W14×109	W14×120	W12×45	HSS7×7×1/2	HSS5-1/2×5-1/2×5/16	5.5
	5	W14×68	W14×74	W12×45	HSS8×8×1/2	HSS5-1/2×5-1/2×5/16	5.5
	6	W14×68	W14×74	W12×45	HSS7×7×1/2	HSS4×4×1/4	3.75
	7	W14×38	W14×43	W12×45	HSS7×7×1/2	HSS4×4×1/4	3.5
	8	W14×38	W14×43	W12×45	HSS5-1/2×5-1/2×5/16	HSS3-1/2×3-1/2×5/16	2.0
	9	W14×22	W14×22	W12×45	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	0.5
Amplified	1	W14×176	W14×193	W12×45	HSS10×10×3/4	n/a	8.5
	2	W14×176	W14×193	W12×45	HSS9×9×5/8	HSS6×6×3/8	5.5
	3	W14×120	W14×120	W12×45	HSS9×9×5/8	HSS5-1/2×5-1/2×3/8	6.5
	4	W14×120	W14×120	W12×45	HSS8×8×1/2	HSS5-1/2×5-1/2×5/16	5.5
	5	W14×74	W14×82	W12×45	HSS8×8×1/2	HSS5-1/2×5-1/2×5/16	5.5
	6	W14×74	W14×82	W12×45	HSS7×7×1/2	HSS4×4×1/4	3.75
	7	W14×38	W14×43	W12×45	HSS7×7×1/2	HSS4×4×1/4	3.5
	8	W14×38	W14×43	W12×45	HSS5-1/2×5-1/2×3/8	HSS4×4×1/4	1.75
	9	W14×22	W14×22	W12×45	HSS4-1/2×4-1/2×5/16	HSS3×3×3/16	0.5
Modal	1	W14×176	W14×193	W12×45	HSS12×12×3/4	n/a	9.5
	2	W14×176	W14×193	W12×45	HSS9×9×5/8	HSS8×8×5/8	5.5
	3	W14×120	W14×109	W14×68	HSS9×9×5/8	HSS8×8×5/8	6.5

Table A.1 (continued)

Archetype	Story	Left Col.	Right Col.	Beam	Brace	Tie	BRB
	4	W14×120	W14×109	W12×45	HSS7×7×1/2	HSS8×8×1/2	5.5
	5	W14×74	W14×61	W12×45	W12×79	HSS7×7×5/8	5.5
	6	W14×74	W14×61	W12×45	HSS7×7×1/2	HSS6×6×1/2	4.5
	7	W14×43	W14×38	W12×45	HSS6×6×3/8	HSS6×6×1/2	3.5
	8	W14×43	W14×38	W12×45	HSS5-1/2×5-1/2×3/8	HSS4×4×1/4	2.25
	9	W14×22	W14×22	W12×45	HSS4×4×5/16	HSS3-1/2×3-1/2×1/4	0.5
Permutation	1	W14×176	W14×176	W14×74	HSS12×12×3/4	n/a	10.0
	2	W14×176	W14×176	W12×45	HSS9×9×5/8	HSS10×10×3/4	5.5
	3	W14×120	W14×109	W14×68	HSS9×9×5/8	HSS10×10×5/8	6.0
	4	W14×120	W14×109	W12×45	HSS7×7×1/2	HSS9×9×5/8	5.5
	5	W14×74	W14×61	W14×53	HSS7×7×1/2	HSS9×9×5/8	5.5
	6	W14×74	W14×61	W12×45	HSS7×7×1/2	HSS7×7×1/2	4.5
	7	W14×43	W14×38	W12×45	HSS5-1/2×5-1/2×3/8	HSS6×6×5/8	3.5
	8	W14×43	W14×38	W12×45	HSS5-1/2×5-1/2×3/8	HSS4×4×3/8	2.25
	9	W14×22	W14×22	W12×45	HSS4×4×5/16	HSS4×4×1/4	0.5
9Xo-30-Dmax							
Basic	1	W14×176	W14×159	W14×68	HSS10×10×3/4	n/a	8.0
	2	W14×176	W14×159	W14×68	HSS6×6×1/2	HSS6×6×1/2	7.5
	3	W14×120	W14×109	W14×68	HSS8×8×1/2	HSS6×6×1/2	7.0
	4	W14×120	W14×109	W14×68	HSS6×6×3/8	HSS5-1/2×5-1/2×3/8	7.0
	5	W14×74	W14×68	W14×68	HSS7×7×1/2	HSS5-1/2×5-1/2×5/16	6.0
	6	W14×74	W14×68	W14×68	HSS5-1/2×5-1/2×3/8	HSS4×4×1/4	5.5
	7	W14×38	W14×43	W14×68	HSS5-1/2×5-1/2×3/8	HSS4×4×1/4	4.0
	8	W14×38	W14×43	W14×68	HSS5×5×5/16	HSS3-1/2×3-1/2×1/4	2.0
	9	W14×22	W14×22	W14×68	HSS3-1/2×3-1/2×1/4	HSS2-1/4×2-1/4×3/16	0.75
Amplified	1	W14×176	W14×176	W14×68	HSS10×10×3/4	n/a	8.0
	2	W14×176	W14×176	W14×68	HSS7×7×1/2	HSS6×6×5/8	7.5
	3	W14×120	W14×109	W14×68	HSS8×8×5/8	HSS6×6×5/8	7.0
	4	W14×120	W14×109	W14×68	HSS6×6×3/8	HSS6×6×3/8	7.0
	5	W14×74	W14×74	W14×68	HSS7×7×1/2	HSS6×6×3/8	6.0
	6	W14×74	W14×74	W14×68	HSS5-1/2×5-1/2×3/8	HSS4×4×1/4	5.5
	7	W14×43	W14×43	W14×68	HSS6×6×3/8	HSS4×4×1/4	4.0
	8	W14×43	W14×43	W14×68	HSS5×5×5/16	HSS3-1/2×3-1/2×1/4	2.0
	9	W14×22	W14×22	W14×68	HSS3-1/2×3-1/2×1/4	HSS2-1/4×2-1/4×3/16	0.75
Modal	1	W14×176	W14×159	W14×68	HSS10×10×3/4	n/a	8.0
	2	W14×176	W14×159	W14×68	HSS7×7×1/2	HSS7×7×1/2	7.5
	3	W14×120	W14×109	W14×68	HSS8×8×5/8	HSS7×7×1/2	7.0
	4	W14×120	W14×109	W14×68	HSS5-1/2×5-1/2×3/8	HSS7×7×1/2	7.0
	5	W14×74	W14×61	W14×68	HSS7×7×1/2	HSS6×6×5/8	6.0
	6	W14×74	W14×61	W14×68	HSS6×6×3/8	HSS5-1/2×5-1/2×3/8	5.5
	7	W14×43	W14×43	W14×68	HSS5-1/2×5-1/2×5/16	HSS5-1/2×5-1/2×5/16	4.0
	8	W14×43	W14×43	W14×68	HSS5×5×5/16	HSS4×4×1/4	2.25
	9	W14×22	W14×22	W14×68	HSS4×4×1/4	HSS3-1/2×3-1/2×1/4	0.75
Permutation	1	W14×176	W14×176	W18×86	HSS12×12×3/4	n/a	8.0
	2	W14×176	W14×176	W14×68	HSS7×7×1/2	HSS9×9×5/8	7.5
	3	W14×120	W14×109	W14×74	HSS8×8×1/2	HSS9×9×5/8	7.0
	4	W14×120	W14×109	W14×68	HSS6×6×1/2	HSS8×8×5/8	7.0

Table A.1 (continued)

Archetype	**Story**	**Left Col.**	**Right Col.**	**Beam**	**Brace**	**Tie**	**BRB**
	5	W14×74	W14×61	W14×68	HSS7×7×1/2	HSS8×8×5/8	6.0
	6	W14×74	W14×61	W14×68	HSS6×6×3/8	HSS6×6×1/2	5.5
	7	W14×43	W14×38	W14×68	HSS5×5×5/16	HSS6×6×1/2	4.0
	8	W14×43	W14×38	W14×68	HSS5×5×5/16	HSS4×4×5/16	2.5
	9	W14×22	W14×22	W14×68	HSS3-1/2×3-1/2×1/4	HSS3-1/2×3-1/2×1/4	0.75

Table A.2: Takeoff results

Archetype	Base shear (kip)	BRB volume (in.^{3})	Steel weight (lb)	BRB volume per base shear (in.^{3}/kip)	Steel weight per base shear (lbf/kip)
2C-20-Dmax					
Basic	33.9	3226	344	95.3	10.17
Amplified	33.9	3338	344	98.6	10.17
Modal	33.9	3402	344	100.5	10.17
Permutation	33.9	3402	344	100.5	10.17
2C-20-Dmin					
Basic	16.9	3024	197	178.6	11.62
Amplified	16.9	3059	197	180.7	11.62
Modal	16.9	3084	197	182.1	11.62
Permutation	16.9	3049	197	180.1	11.62
2C-30-Dmax					
Basic	71.6	5316	715	74.3	9.99
Amplified	71.6	5495	715	76.8	9.99
Modal	71.6	5385	715	75.3	9.99
Permutation	71.6	5385	715	75.3	9.99
2C-30-Dmin					
Basic	35.8	5090	417	142.3	11.65
Amplified	35.8	5132	417	143.5	11.65
Modal	35.8	5196	417	145.3	11.65
Permutation	35.8	5196	417	145.3	11.65
2X-20-Dmax					
Basic	33.9	3265	344	96.4	10.17
Amplified	33.9	3265	344	96.4	10.17
Modal	33.9	3265	344	96.4	10.17
Permutation	33.9	3265	344	96.4	10.17
2X-20-Dmin					
Basic	16.9	2995	197	176.9	11.62
Amplified	16.9	2995	197	176.9	11.62
Modal	16.9	2995	197	176.9	11.62
Permutation	16.9	2995	197	176.9	11.62
2X-30-Dmax					
Basic	71.6	5184	655	72.5	9.15
Amplified	71.6	5381	715	75.2	9.99
Modal	71.6	5184	655	72.5	9.15
Permutation	71.6	5184	655	72.5	9.15
2X-30-Dmin					
Basic	35.8	5018	417	140.3	11.65
Amplified	35.8	5018	417	140.3	11.65
Modal	35.8	5018	417	140.3	11.65
Permutation	35.8	5018	417	140.3	11.65
2Xo-20-Dmax					
Basic	33.9	3449	391	101.9	11.55
Amplified	33.9	3553	391	104.9	11.55
Modal	33.9	3553	391	104.9	11.55
Permutation	33.9	3553	391	104.9	11.55

Table A.2 (continued)

Archetype	Base shear (kip)	BRB volume (in.^{3})	Steel weight (lb)	BRB volume per base shear ($\mathrm{in.^3/kip}$)	Steel weight per base shear ($\mathrm{lbf/kip}$)
2Xo-20-Dmin					
Basic	16.9	3223	223	190.3	13.20
Amplified	16.9	3251	223	192.0	13.20
Modal	16.9	3251	223	192.0	13.20
Permutation	16.9	3223	223	190.3	13.20
2Xo-30-Dmax					
Basic	71.6	6266	859	87.6	12.00
Amplified	71.6	6266	859	87.6	12.00
Modal	71.6	6266	859	87.6	12.00
Permutation	71.6	6266	859	87.6	12.00
2Xo-30-Dmax-Heavy					
Basic	98.1	6362	1145	64.8	11.67
Amplified	98.1	6362	1145	64.8	11.67
Modal	98.1	6362	1145	64.8	11.67
Permutation	98.1	6362	1145	64.8	11.67
2Xo-30-Dmin					
Basic	35.8	6118	501	171.0	14.00
Amplified	35.8	6153	501	172.0	14.00
Modal	35.8	6118	501	171.0	14.00
Permutation	35.8	6118	501	171.0	14.00
3C-20-Dmax					
Basic	59.0	5265	738	89.3	12.51
Amplified	59.0	5299	738	89.8	12.51
Modal	59.0	5454	738	92.5	12.51
Permutation	59.0	5476	738	92.8	12.51
3C-20-Dmin					
Basic	25.2	5012	394	198.9	15.62
Amplified	25.2	5090	394	202.0	15.62
Modal	25.2	5166	394	205.0	15.62
Permutation	25.2	5191	394	206.0	15.62
3C-30-Dmax					
Basic	124.4	9064	1548	72.8	12.44
Amplified	124.4	9086	1548	73.0	12.44
Modal	124.4	9226	1608	74.1	12.92
Permutation	124.4	9282	1608	74.6	12.92
3C-30-Dmin					
Basic	53.2	7984	834	150.2	15.68
Amplified	53.2	8138	834	153.1	15.68
Modal	53.2	8261	834	155.4	15.68
Permutation	53.2	8448	893	158.9	16.81
3X-20-Dmax					
Basic	59.0	5287	787	89.6	13.35
Amplified	59.0	5414	787	91.8	13.35
Modal	59.0	5429	787	92.0	13.35
Permutation	59.0	5456	787	92.5	13.35

Table A.2 (continued)

Archetype	Base shear (kip)	BRB volume (in.^{3})	Steel weight (lb)	BRB volume per base shear ($^{\text{in.}^3}/_{\text{kip}}$)	Steel weight per base shear ($^{\text{lbf}}/_{\text{kip}}$)
3X-20-Dmin					
Basic	25.2	5071	394	201.3	15.62
Amplified	25.2	5071	394	201.3	15.62
Modal	25.2	5080	394	201.6	15.62
Permutation	25.2	5144	394	204.1	15.62
3X-30-Dmax					
Basic	124.4	8978	1608	72.2	12.92
Amplified	124.4	9174	1608	73.7	12.92
Modal	124.4	9047	1608	72.7	12.92
Permutation	124.4	9131	1608	73.4	12.92
3X-30-Dmin					
Basic	53.2	8152	893	153.4	16.81
Amplified	53.2	8287	893	155.9	16.81
Modal	53.2	8224	893	154.7	16.81
Permutation	53.2	8247	893	155.2	16.81
3Xo-20-Dmax					
Basic	59.0	5682	950	96.3	16.10
Amplified	59.0	5719	950	97.0	16.10
Modal	59.0	5792	950	98.2	16.10
Permutation	59.0	5792	950	98.2	16.10
3Xo-20-Dmax-Tall					
Basic	59.0	7138	1119	121.0	18.97
Amplified	59.0	7269	1119	123.2	18.97
Modal	59.0	7147	1119	121.2	18.97
Permutation	59.0	7211	1119	122.2	18.97
3Xo-20-Dmin					
Basic	25.2	5487	503	217.8	19.95
Amplified	25.2	5518	503	219.0	19.95
Modal	25.2	5521	503	219.1	19.95
Permutation	25.2	5521	503	219.1	19.95
3Xo-30-Dmax					
Basic	124.4	10375	2218	83.4	17.83
Amplified	124.4	10445	2218	83.9	17.83
Modal	124.4	10469	2218	84.1	17.83
Permutation	124.4	10469	2218	84.1	17.83
3Xo-30-Dmax-Tall					
Basic	124.4	11621	2455	93.4	19.73
Amplified	124.4	12024	2455	96.6	19.73
Modal	124.4	11672	2455	93.8	19.73
Permutation	124.4	11672	2455	93.8	19.73
3Xo-30-Dmin					
Basic	53.2	9521	1145	179.1	21.54
Amplified	53.2	9590	1145	180.4	21.54
Modal	53.2	9545	1145	179.6	21.54
Permutation	53.2	9545	1145	179.6	21.54

Table A.2 (continued)

Archetype	Base shear (kip)	BRB volume (in.^{3})	Steel weight (lb)	BRB volume per base shear ($^{\text{in.}^3}/_{\text{kip}}$)	Steel weight per base shear ($^{\text{lbf}}/_{\text{kip}}$)
4C-20-Dmax					
Basic	84.1	7962	1279	94.7	15.21
Amplified	84.1	7974	1279	94.8	15.21
Modal	84.1	8370	1279	99.5	15.21
Permutation	84.1	8419	1279	100.1	15.21
4C-20-Dmin					
Basic	29.0	6738	590	232.7	20.39
Amplified	29.0	6894	590	238.1	20.39
Modal	29.0	6954	590	240.1	20.39
Permutation	29.0	7117	590	245.8	20.39
4C-30-Dmax					
Basic	177.3	13402	2739	75.6	15.45
Amplified	177.3	13467	2739	76.0	15.45
Modal	177.3	13989	2858	78.9	16.12
Permutation	177.3	13939	2858	78.6	16.12
4C-30-Dmin					
Basic	61.0	11720	1310	192.0	21.46
Amplified	61.0	11788	1310	193.1	21.46
Modal	61.0	12027	1310	197.0	21.46
Permutation	61.0	12027	1310	197.0	21.46
4X-20-Dmax					
Basic	84.1	7978	1476	94.9	17.55
Amplified	84.1	8013	1476	95.3	17.55
Modal	84.1	8310	1476	98.8	17.55
Permutation	84.1	8310	1476	98.8	17.55
4X-20-Dmin					
Basic	29.0	6734	640	232.5	22.09
Amplified	29.0	6934	640	239.4	22.09
Modal	29.0	6824	640	235.7	22.09
Permutation	29.0	7032	689	242.8	23.79
4X-30-Dmax					
Basic	177.3	13432	2918	75.8	16.46
Amplified	177.3	13643	2918	76.9	16.46
Modal	177.3	13864	3037	78.2	17.13
Permutation	177.3	14187	3037	80.0	17.13
4X-30-Dmin					
Basic	61.0	11622	1310	190.4	21.46
Amplified	61.0	11622	1310	190.4	21.46
Modal	61.0	11753	1310	192.5	21.46
Permutation	61.0	11753	1310	192.5	21.46
4Xo-20-Dmax					
Basic	84.1	8530	1788	101.4	21.25
Amplified	84.1	8681	1788	103.2	21.25
Modal	84.1	8667	1788	103.0	21.25
Permutation	84.1	8667	1788	103.0	21.25

Table A.2 (continued)

Archetype	**Base shear (kip)**	**BRB volume (in.^{3})**	**Steel weight (lb)**	**BRB volume per base shear ($^{in.^3}/_{kip}$)**	**Steel weight per base shear ($^{lbf}/_{kip}$)**
4Xo-20-Dmin					
Basic	29.0	7329	782	253.1	27.01
Amplified	29.0	7337	782	253.4	27.01
Modal	29.0	7446	782	257.1	27.01
Permutation	29.0	7446	782	257.1	27.01
4Xo-30-Dmax					
Basic	177.3	14954	3936	84.3	22.20
Amplified	177.3	14989	3936	84.5	22.20
Modal	177.3	15217	3936	85.8	22.20
Permutation	177.3	15217	3936	85.8	22.20
4Xo-30-Dmax-Heavy					
Basic	257.0	15887	5439	61.8	21.16
Amplified	257.0	16223	5439	63.1	21.16
Modal	257.0	16601	5582	64.6	21.72
Permutation	257.0	16656	5582	64.8	21.72
4Xo-30-Dmin					
Basic	61.0	13489	1717	221.0	28.14
Amplified	61.0	13551	1717	222.0	28.14
Modal	61.0	13670	1789	223.9	29.31
Permutation	61.0	13670	1789	223.9	29.31
6C-20-Dmax					
Basic	109.7	14165	2509	129.1	22.88
Amplified	109.7	14449	2509	131.7	22.88
Modal	109.7	14651	2509	133.6	22.88
Permutation	109.7	14953	2559	136.3	23.32
6C-20-Dmin					
Basic	34.1	11187	1033	327.8	30.28
Amplified	34.1	11297	1033	331.0	30.28
Modal	34.1	11521	1082	337.6	31.72
Permutation	34.1	11569	1082	339.0	31.72
6C-30-Dmax					
Basic	231.1	24093	5300	104.3	22.93
Amplified	231.1	24585	5300	106.4	22.93
Modal	231.1	25770	5419	111.5	23.45
Permutation	231.1	25976	5359	112.4	23.19
6C-30-Dmin					
Basic	71.9	18965	2144	263.8	29.82
Amplified	71.9	19236	2144	267.6	29.82
Modal	71.9	19495	2203	271.2	30.65
Permutation	71.9	19893	2263	276.7	31.47
6X-20-Dmax					
Basic	109.7	15153	2854	138.1	26.02
Amplified	109.7	14772	2805	134.7	25.57
Modal	109.7	15047	2854	137.2	26.02
Permutation	109.7	15393	2903	140.3	26.46

Table A.2 (continued)

Archetype	**Base shear (kip)**	**BRB volume (in.^{3})**	**Steel weight (lb)**	**BRB volume per base shear ($^{\text{in.}^3}/_{\text{kip}}$)**	**Steel weight per base shear ($^{\text{lbf}}/_{\text{kip}}$)**
6X-20-Dmin					
Basic	34.1	11591	1132	339.6	33.16
Amplified	34.1	11431	1181	335.0	34.60
Modal	34.1	11596	1181	339.8	34.60
Permutation	34.1	11639	1181	341.0	34.60
6X-30-Dmax					
Basic	231.1	24217	5538	104.8	23.96
Amplified	231.1	24660	5657	106.7	24.48
Modal	231.1	25347	5717	109.7	24.74
Permutation	231.1	26317	5717	113.9	24.74
6X-30-Dmin					
Basic	71.9	19066	2382	265.2	33.13
Amplified	71.9	19390	2382	269.7	33.13
Modal	71.9	19435	2441	270.3	33.96
Permutation	71.9	19654	2501	273.4	34.79
6Xo-20-Dmax					
Basic	109.7	15122	3464	137.8	31.57
Amplified	109.7	15293	3464	139.4	31.57
Modal	109.7	15457	3464	140.9	31.57
Permutation	109.7	15520	3464	141.5	31.57
6Xo-20-Dmax-Tall					
Basic	104.7	17330	3656	165.5	34.92
Amplified	104.7	17560	3656	167.7	34.92
Modal	104.7	17717	3656	169.2	34.92
Permutation	104.7	17692	3656	169.0	34.92
6Xo-20-Dmin					
Basic	34.1	12010	1341	351.9	39.29
Amplified	34.1	12298	1341	360.3	39.29
Modal	34.1	12178	1341	356.8	39.29
Permutation	34.1	12444	1397	364.6	40.92
6Xo-30-Dmax					
Basic	231.1	26615	7800	115.2	33.75
Amplified	231.1	26934	7800	116.6	33.75
Modal	231.1	27355	7872	118.4	34.06
Permutation	231.1	27714	7943	119.9	34.37
6Xo-30-Dmax-Tall					
Basic	220.6	28290	7932	128.3	35.96
Amplified	220.6	28516	7932	129.3	35.96
Modal	220.6	28553	8075	129.4	36.61
Permutation	220.6	29092	8075	131.9	36.61
6Xo-30-Dmin					
Basic	71.9	21830	3149	303.6	43.80
Amplified	71.9	22252	3149	309.5	43.80
Modal	71.9	22057	3149	306.8	43.80
Permutation	71.9	22188	3220	308.6	44.79

Table A.2 (continued)

Archetype	**Base shear (kip)**	**BRB volume (in.^{3})**	**Steel weight (lb)**	**BRB volume per base shear (in.^{3}/kip)**	**Steel weight per base shear (lbf/kip)**
9X-30-Dmax					
Basic	266.0	44323	9825	166.6	36.93
Amplified	266.0	45425	9766	170.7	36.71
Modal	266.0	48072	10302	180.7	38.72
Permutation	266.0	49305	10302	185.3	38.72
9Xo-30-Dmax					
Basic	266.0	46719	13668	175.6	51.38
Amplified	266.0	48071	13668	180.7	51.38
Modal	266.0	47968	13740	180.3	51.64
Permutation	266.0	50735	13811	190.7	51.91

Table A.3: Drift ratios

Archetype	Story	Maximum first-order story drift ratio (%)	Maximum second-order story drift ratio (%)	Second-to-first-order drift ratio
2C-20-Dmax				
Amplified	1	0.474	0.478	1.009
	2	0.399	0.401	1.005
Basic	1	0.476	0.480	1.009
	2	0.411	0.413	1.005
Modal	1	0.477	0.481	1.009
	2	0.392	0.394	1.005
Permutation	1	0.477	0.481	1.009
	2	0.392	0.394	1.005
2C-20-Dmin				
Amplified	1	0.409	0.414	1.012
	2	0.338	0.341	1.008
Basic	1	0.413	0.418	1.012
	2	0.337	0.340	1.008
Modal	1	0.410	0.415	1.012
	2	0.335	0.338	1.008
Permutation	1	0.414	0.420	1.012
	2	0.334	0.337	1.008
2C-30-Dmax				
Amplified	1	0.505	0.510	1.009
	2	0.428	0.430	1.005
Basic	1	0.519	0.524	1.010
	2	0.429	0.431	1.005
Modal	1	0.522	0.527	1.010
	2	0.418	0.420	1.005
Permutation	1	0.522	0.527	1.010
	2	0.418	0.420	1.005
2C-30-Dmin				
Amplified	1	0.465	0.471	1.014
	2	0.359	0.362	1.008
Basic	1	0.464	0.471	1.014
	2	0.364	0.367	1.008
Modal	1	0.467	0.473	1.014
	2	0.353	0.356	1.008
Permutation	1	0.467	0.473	1.014
	2	0.353	0.356	1.008
2X-20-Dmax				
Amplified	1	0.467	0.471	1.009
	2	0.410	0.412	1.005
Basic	1	0.467	0.471	1.009
	2	0.410	0.412	1.005

Table A.3 (continued)

Archetype	**Story**	**Maximum first-order story drift ratio (%)**	**Maximum second-order story drift ratio (%)**	**Second-to-first-order drift ratio**
Modal	1	0.467	0.471	1.009
	2	0.410	0.412	1.005
Permutation	1	0.467	0.471	1.009
	2	0.410	0.412	1.005
2X-20-Dmin				
Amplified	1	0.402	0.407	1.012
	2	0.326	0.328	1.007
Basic	1	0.402	0.407	1.012
	2	0.326	0.328	1.007
Modal	1	0.407	0.412	1.012
	2	0.332	0.334	1.008
Permutation	1	0.407	0.412	1.012
	2	0.332	0.334	1.008
2X-30-Dmax				
Amplified	1	0.477	0.481	1.009
	2	0.400	0.402	1.004
Basic	1	0.534	0.540	1.011
	2	0.406	0.407	1.004
Modal	1	0.534	0.540	1.011
	2	0.406	0.407	1.004
Permutation	1	0.534	0.540	1.011
	2	0.406	0.407	1.004
2X-30-Dmin				
Amplified	1	0.445	0.451	1.014
	2	0.284	0.286	1.008
Basic	1	0.445	0.451	1.014
	2	0.284	0.286	1.008
Modal	1	0.445	0.451	1.014
	2	0.284	0.286	1.008
Permutation	1	0.445	0.451	1.014
	2	0.284	0.286	1.008
2Xo-20-Dmax				
Amplified	1	0.574	0.580	1.011
	2	0.544	0.548	1.007
Basic	1	0.576	0.582	1.011
	2	0.537	0.540	1.007
Modal	1	0.574	0.580	1.011
	2	0.544	0.548	1.007
Permutation	1	0.574	0.580	1.011
	2	0.544	0.548	1.007

Table A.3 (continued)

Archetype	Story	Maximum first-order story drift ratio (%)	Maximum second-order story drift ratio (%)	Second-to-first-order drift ratio
2Xo-20-Dmin				
Amplified	1	0.511	0.520	1.016
	2	0.453	0.458	1.011
Basic	1	0.509	0.518	1.016
	2	0.471	0.476	1.011
Modal	1	0.511	0.520	1.016
	2	0.453	0.458	1.011
Permutation	1	0.509	0.518	1.016
	2	0.471	0.476	1.011
2Xo-30-Dmax				
Amplified	1	0.665	0.674	1.012
	2	0.611	0.615	1.008
Basic	1	0.665	0.674	1.012
	2	0.611	0.615	1.008
Modal	1	0.665	0.674	1.012
	2	0.611	0.615	1.008
Permutation	1	0.665	0.674	1.012
	2	0.611	0.615	1.008
2Xo-30-Dmax-Heavy				
Amplified	1	0.652	0.661	1.013
	2	0.600	0.604	1.007
Basic	1	0.652	0.661	1.013
	2	0.600	0.604	1.007
Modal	1	0.652	0.661	1.013
	2	0.600	0.604	1.007
Permutation	1	0.652	0.661	1.013
	2	0.600	0.604	1.007
2Xo-30-Dmin				
Amplified	1	0.624	0.635	1.018
	2	0.472	0.479	1.014
Basic	1	0.624	0.636	1.019
	2	0.472	0.479	1.014
Modal	1	0.624	0.636	1.019
	2	0.472	0.479	1.014
Permutation	1	0.624	0.636	1.019
	2	0.472	0.479	1.014
3C-20-Dmax				
Amplified	1	0.546	0.552	1.011
	2	0.668	0.674	1.010
	3	0.527	0.531	1.007
Basic	1	0.545	0.551	1.011

Table A.3 (continued)

Archetype	**Story**	**Maximum first-order story drift ratio (%)**	**Maximum second-order story drift ratio (%)**	**Second-to-first-order drift ratio**
	2	0.685	0.693	1.010
	3	0.525	0.529	1.007
Modal	1	0.560	0.566	1.011
	2	0.671	0.678	1.011
	3	0.537	0.541	1.007
Permutation	1	0.561	0.567	1.011
	2	0.672	0.679	1.011
	3	0.539	0.543	1.007
3C-20-Dmin				
Amplified	1	0.455	0.463	1.017
	2	0.450	0.456	1.014
	3	0.355	0.359	1.010
Basic	1	0.457	0.465	1.017
	2	0.463	0.470	1.015
	3	0.352	0.355	1.010
Modal	1	0.468	0.476	1.016
	2	0.458	0.465	1.015
	3	0.340	0.344	1.011
Permutation	1	0.468	0.476	1.016
	2	0.459	0.465	1.015
	3	0.336	0.340	1.011
3C-30-Dmax				
Amplified	1	0.601	0.609	1.012
	2	0.656	0.663	1.010
	3	0.512	0.515	1.007
Basic	1	0.601	0.609	1.012
	2	0.655	0.662	1.010
	3	0.516	0.519	1.007
Modal	1	0.589	0.595	1.012
	2	0.636	0.643	1.010
	3	0.515	0.518	1.007
Permutation	1	0.589	0.596	1.012
	2	0.638	0.645	1.010
	3	0.518	0.521	1.007
3C-30-Dmin				
Amplified	1	0.466	0.474	1.017
	2	0.542	0.550	1.016
	3	0.379	0.383	1.011
Basic	1	0.470	0.478	1.018
	2	0.541	0.550	1.016
	3	0.379	0.383	1.011
Modal	1	0.479	0.487	1.017
	2	0.526	0.535	1.016

Table A.3 (continued)

Archetype	Story	Maximum first-order story drift ratio (%)	Maximum second-order story drift ratio (%)	Second-to-first-order drift ratio
	3	0.361	0.365	1.011
Permutation	1	0.440	0.447	1.015
	2	0.514	0.523	1.016
	3	0.341	0.345	1.011
3X-20-Dmax				
Amplified	1	0.477	0.481	1.009
	2	0.757	0.766	1.011
	3	0.645	0.650	1.008
Basic	1	0.493	0.498	1.009
	2	0.749	0.758	1.011
	3	0.644	0.649	1.008
Modal	1	0.497	0.501	1.009
	2	0.746	0.754	1.011
	3	0.624	0.630	1.008
Permutation	1	0.497	0.502	1.009
	2	0.746	0.755	1.011
	3	0.608	0.613	1.008
3X-20-Dmin				
Amplified	1	0.418	0.424	1.015
	2	0.521	0.530	1.017
	3	0.423	0.427	1.011
Basic	1	0.416	0.422	1.015
	2	0.519	0.527	1.017
	3	0.421	0.426	1.011
Modal	1	0.418	0.424	1.015
	2	0.521	0.530	1.017
	3	0.422	0.427	1.011
Permutation	1	0.421	0.427	1.015
	2	0.516	0.524	1.017
	3	0.408	0.413	1.012
3X-30-Dmax				
Amplified	1	0.500	0.505	1.010
	2	0.640	0.646	1.010
	3	0.627	0.631	1.007
Basic	1	0.496	0.501	1.010
	2	0.683	0.691	1.011
	3	0.631	0.635	1.007
Modal	1	0.497	0.502	1.010
	2	0.682	0.689	1.011
	3	0.617	0.622	1.007
Permutation	1	0.499	0.504	1.010
	2	0.680	0.687	1.011

Table A.3 (continued)

Archetype	Story	Maximum first-order story drift ratio (%)	Maximum second-order story drift ratio (%)	Second-to-first-order drift ratio
	3	0.601	0.605	1.008
3X-30-Dmin				
Amplified	1	0.403	0.409	1.014
	2	0.498	0.507	1.017
	3	0.432	0.437	1.010
Basic	1	0.400	0.406	1.014
	2	0.491	0.499	1.017
	3	0.433	0.437	1.010
Modal	1	0.402	0.407	1.014
	2	0.488	0.496	1.017
	3	0.419	0.424	1.011
Permutation	1	0.402	0.407	1.014
	2	0.488	0.496	1.017
	3	0.418	0.422	1.011
3Xo-20-Dmax				
Amplified	1	0.569	0.575	1.011
	2	0.829	0.841	1.014
	3	0.786	0.793	1.009
Basic	1	0.574	0.580	1.011
	2	0.829	0.841	1.014
	3	0.786	0.793	1.009
Modal	1	0.579	0.585	1.011
	2	0.803	0.813	1.013
	3	0.778	0.785	1.009
Permutation	1	0.579	0.585	1.011
	2	0.803	0.813	1.013
	3	0.778	0.785	1.009
3Xo-20-Dmax-Tall				
Amplified	1	0.617	0.624	1.012
	2	0.747	0.756	1.012
	3	0.707	0.713	1.009
Basic	1	0.630	0.638	1.012
	2	0.744	0.753	1.012
	3	0.707	0.713	1.009
Modal	1	0.630	0.638	1.012
	2	0.744	0.753	1.012
	3	0.706	0.712	1.009
Permutation	1	0.631	0.639	1.012
	2	0.741	0.750	1.012
	3	0.694	0.700	1.009
3Xo-20-Dmin				
Amplified	1	0.487	0.495	1.017
	2	0.553	0.564	1.019

Table A.3 (continued)

Archetype	Story	Maximum first-order story drift ratio (%)	Maximum second-order story drift ratio (%)	Second-to-first-order drift ratio
	3	0.581	0.589	1.014
Basic	1	0.486	0.495	1.018
	2	0.550	0.561	1.019
	3	0.581	0.589	1.013
Modal	1	0.488	0.497	1.018
	2	0.548	0.558	1.019
	3	0.571	0.579	1.014
Permutation	1	0.488	0.497	1.018
	2	0.548	0.558	1.019
	3	0.571	0.579	1.014
3Xo-30-Dmax				
Amplified	1	0.621	0.628	1.011
	2	0.826	0.837	1.013
	3	0.733	0.739	1.008
Basic	1	0.619	0.626	1.011
	2	0.838	0.849	1.014
	3	0.738	0.744	1.008
Modal	1	0.620	0.627	1.011
	2	0.836	0.847	1.014
	3	0.728	0.734	1.008
Permutation	1	0.620	0.627	1.011
	2	0.836	0.847	1.014
	3	0.728	0.734	1.008
3Xo-30-Dmax-Tall				
Amplified	1	0.593	0.599	1.011
	2	0.797	0.807	1.013
	3	0.660	0.665	1.008
Basic	1	0.596	0.603	1.011
	2	0.815	0.825	1.013
	3	0.680	0.685	1.008
Modal	1	0.597	0.603	1.011
	2	0.810	0.821	1.013
	3	0.683	0.689	1.008
Permutation	1	0.597	0.603	1.011
	2	0.810	0.821	1.013
	3	0.683	0.689	1.008
3Xo-30-Dmin				
Amplified	1	0.548	0.558	1.018
	2	0.663	0.677	1.022
	3	0.602	0.611	1.014
Basic	1	0.543	0.553	1.019
	2	0.656	0.670	1.022
	3	0.608	0.617	1.014

Table A.3 (continued)

Archetype	**Story**	**Maximum first-order story drift ratio (%)**	**Maximum second-order story drift ratio (%)**	**Second-to-first-order drift ratio**
Modal	1	0.543	0.553	1.019
	2	0.656	0.670	1.022
	3	0.606	0.614	1.014
Permutation	1	0.543	0.553	1.019
	2	0.656	0.670	1.022
	3	0.606	0.614	1.014
4C-20-Dmax				
Amplified	1	0.567	0.573	1.011
	2	0.838	0.850	1.014
	3	0.883	0.894	1.012
	4	0.707	0.713	1.010
Basic	1	0.567	0.573	1.011
	2	0.838	0.850	1.014
	3	0.874	0.885	1.012
	4	0.724	0.731	1.010
Modal	1	0.584	0.590	1.011
	2	0.836	0.848	1.014
	3	0.880	0.891	1.013
	4	0.740	0.747	1.010
Permutation	1	0.585	0.592	1.011
	2	0.835	0.847	1.014
	3	0.879	0.891	1.013
	4	0.743	0.750	1.010
4C-20-Dmin				
Amplified	1	0.445	0.455	1.020
	2	0.507	0.518	1.021
	3	0.566	0.577	1.020
	4	0.409	0.416	1.016
Basic	1	0.454	0.464	1.021
	2	0.525	0.537	1.021
	3	0.594	0.606	1.020
	4	0.439	0.446	1.017
Modal	1	0.467	0.477	1.020
	2	0.525	0.536	1.021
	3	0.568	0.579	1.021
	4	0.415	0.422	1.017
Permutation	1	0.466	0.476	1.020
	2	0.503	0.514	1.021
	3	0.539	0.550	1.020
	4	0.425	0.431	1.015
4C-30-Dmax				
Amplified	1	0.647	0.656	1.014
	2	0.814	0.825	1.014
	3	0.821	0.830	1.011

Table A.3 (continued)

Archetype	Story	Maximum first-order story drift ratio (%)	Maximum second-order story drift ratio (%)	Second-to-first-order drift ratio
	4	0.665	0.670	1.008
Basic	1	0.647	0.656	1.014
	2	0.814	0.825	1.014
	3	0.819	0.828	1.011
	4	0.674	0.680	1.008
Modal	1	0.635	0.644	1.013
	2	0.806	0.817	1.014
	3	0.777	0.785	1.011
	4	0.698	0.704	1.008
Permutation	1	0.635	0.644	1.013
	2	0.801	0.812	1.014
	3	0.833	0.843	1.012
	4	0.685	0.690	1.008
4C-30-Dmin				
Amplified	1	0.446	0.455	1.020
	2	0.554	0.567	1.022
	3	0.549	0.560	1.019
	4	0.370	0.376	1.015
Basic	1	0.444	0.453	1.020
	2	0.548	0.560	1.022
	3	0.568	0.579	1.019
	4	0.377	0.382	1.014
Modal	1	0.465	0.475	1.020
	2	0.551	0.564	1.022
	3	0.532	0.543	1.020
	4	0.344	0.348	1.013
Permutation	1	0.465	0.475	1.020
	2	0.551	0.564	1.022
	3	0.532	0.543	1.020
	4	0.344	0.348	1.013
4X-20-Dmax				
Amplified	1	0.475	0.479	1.008
	2	0.922	0.937	1.016
	3	0.931	0.943	1.013
	4	0.799	0.807	1.010
Basic	1	0.472	0.476	1.008
	2	0.941	0.956	1.016
	3	0.930	0.942	1.013
	4	0.798	0.806	1.011
Modal	1	0.480	0.484	1.008
	2	0.934	0.949	1.016
	3	0.925	0.937	1.013
	4	0.818	0.827	1.010
Permutation	1	0.480	0.484	1.008

Table A.3 (continued)

Archetype	Story	Maximum first-order story drift ratio (%)	Maximum second-order story drift ratio (%)	Second-to-first-order drift ratio
	2	0.934	0.949	1.016
	3	0.925	0.937	1.013
	4	0.818	0.827	1.010
4X-20-Dmin				
Amplified	1	0.419	0.427	1.017
	2	0.597	0.611	1.023
	3	0.550	0.561	1.019
	4	0.438	0.445	1.016
Basic	1	0.422	0.430	1.018
	2	0.594	0.609	1.024
	3	0.582	0.593	1.019
	4	0.421	0.428	1.016
Modal	1	0.435	0.442	1.017
	2	0.630	0.646	1.025
	3	0.549	0.560	1.020
	4	0.488	0.496	1.016
Permutation	1	0.376	0.382	1.016
	2	0.597	0.611	1.024
	3	0.529	0.539	1.019
	4	0.468	0.475	1.015
4X-30-Dmax				
Amplified	1	0.495	0.500	1.009
	2	0.799	0.810	1.014
	3	0.868	0.878	1.012
	4	0.676	0.681	1.007
Basic	1	0.504	0.509	1.010
	2	0.794	0.805	1.014
	3	0.867	0.877	1.012
	4	0.687	0.692	1.008
Modal	1	0.482	0.486	1.009
	2	0.776	0.787	1.014
	3	0.823	0.832	1.012
	4	0.703	0.708	1.007
Permutation	1	0.483	0.487	1.009
	2	0.743	0.754	1.014
	3	0.798	0.807	1.011
	4	0.677	0.682	1.007
4X-30-Dmin				
Amplified	1	0.395	0.402	1.017
	2	0.582	0.597	1.025
	3	0.616	0.628	1.020
	4	0.360	0.366	1.016
Basic	1	0.395	0.402	1.017
	2	0.582	0.597	1.025

Table A.3 (continued)

Archetype	Story	Maximum first-order story drift ratio (%)	Maximum second-order story drift ratio (%)	Second-to-first-order drift ratio
	3	0.616	0.628	1.020
	4	0.360	0.366	1.016
Modal	1	0.404	0.411	1.016
	2	0.591	0.607	1.027
	3	0.575	0.587	1.020
	4	0.388	0.394	1.014
Permutation	1	0.404	0.411	1.016
	2	0.591	0.607	1.027
	3	0.575	0.587	1.020
	4	0.388	0.394	1.014
4Xo-20-Dmax				
Amplified	1	0.571	0.577	1.010
	2	0.926	0.940	1.016
	3	0.944	0.957	1.013
	4	0.875	0.884	1.011
Basic	1	0.575	0.581	1.010
	2	0.938	0.954	1.017
	3	0.983	0.997	1.013
	4	0.914	0.925	1.012
Modal	1	0.579	0.585	1.010
	2	0.954	0.970	1.016
	3	0.989	1.003	1.014
	4	0.926	0.937	1.011
Permutation	1	0.579	0.585	1.010
	2	0.954	0.970	1.016
	3	0.989	1.003	1.014
	4	0.926	0.937	1.011
4Xo-20-Dmin				
Amplified	1	0.486	0.497	1.021
	2	0.680	0.699	1.028
	3	0.656	0.670	1.022
	4	0.557	0.567	1.019
Basic	1	0.486	0.496	1.021
	2	0.680	0.699	1.028
	3	0.657	0.671	1.022
	4	0.556	0.566	1.019
Modal	1	0.493	0.504	1.021
	2	0.667	0.686	1.029
	3	0.645	0.660	1.023
	4	0.574	0.585	1.019
Permutation	1	0.493	0.504	1.021
	2	0.667	0.686	1.029
	3	0.645	0.660	1.023
	4	0.574	0.585	1.019

Table A.3 (continued)

Archetype	**Story**	**Maximum first-order story drift ratio (%)**	**Maximum second-order story drift ratio (%)**	**Second-to-first-order drift ratio**
4Xo-30-Dmax				
Amplified	1	0.654	0.662	1.012
	2	0.964	0.981	1.017
	3	0.980	0.992	1.013
	4	0.774	0.782	1.009
Basic	1	0.654	0.662	1.012
	2	0.964	0.981	1.017
	3	0.979	0.991	1.013
	4	0.784	0.791	1.010
Modal	1	0.661	0.669	1.012
	2	0.946	0.962	1.017
	3	0.973	0.986	1.013
	4	0.808	0.815	1.009
Permutation	1	0.661	0.669	1.012
	2	0.946	0.962	1.017
	3	0.973	0.986	1.013
	4	0.808	0.815	1.009
4Xo-30-Dmax-Heavy				
Amplified	1	0.685	0.694	1.013
	2	0.999	1.016	1.018
	3	1.028	1.042	1.013
	4	0.855	0.861	1.008
Basic	1	0.679	0.687	1.012
	2	1.055	1.076	1.019
	3	1.027	1.042	1.014
	4	0.869	0.878	1.010
Modal	1	0.654	0.662	1.012
	2	1.013	1.031	1.018
	3	1.032	1.047	1.014
	4	0.944	0.953	1.010
Permutation	1	0.678	0.686	1.012
	2	0.973	0.990	1.018
	3	1.015	1.029	1.014
	4	0.899	0.907	1.009
4Xo-30-Dmin				
Amplified	1	0.583	0.596	1.023
	2	0.721	0.743	1.030
	3	0.728	0.745	1.023
	4	0.503	0.509	1.011
Basic	1	0.580	0.593	1.023
	2	0.730	0.752	1.031
	3	0.725	0.742	1.023
	4	0.508	0.516	1.017
Modal	1	0.548	0.559	1.021

Table A.3 (continued)

Archetype	**Story**	**Maximum first-order story drift ratio (%)**	**Maximum second-order story drift ratio (%)**	**Second-to-first-order drift ratio**
	2	0.712	0.735	1.031
	3	0.697	0.713	1.023
	4	0.527	0.537	1.018
Permutation	1	0.548	0.559	1.021
	2	0.712	0.735	1.031
	3	0.697	0.713	1.023
	4	0.527	0.537	1.018
6C-20-Dmax				
Amplified	1	0.605	0.614	1.015
	2	0.866	0.883	1.020
	3	1.086	1.109	1.021
	4	1.245	1.272	1.022
	5	1.231	1.255	1.020
	6	1.066	1.086	1.018
Basic	1	0.604	0.613	1.015
	2	0.934	0.954	1.021
	3	1.116	1.141	1.022
	4	1.263	1.291	1.022
	5	1.263	1.289	1.020
	6	1.070	1.089	1.018
Modal	1	0.620	0.629	1.015
	2	0.891	0.910	1.020
	3	1.168	1.196	1.023
	4	1.354	1.385	1.023
	5	1.350	1.379	1.021
	6	1.184	1.206	1.019
Permutation	1	0.580	0.588	1.014
	2	0.942	0.962	1.022
	3	1.174	1.201	1.024
	4	1.353	1.384	1.023
	5	1.352	1.381	1.021
	6	1.190	1.212	1.019
6C-20-Dmin				
Amplified	1	0.464	0.478	1.029
	2	0.591	0.612	1.035
	3	0.692	0.717	1.036
	4	0.759	0.787	1.037
	5	0.729	0.754	1.034
	6	0.565	0.583	1.032
Basic	1	0.466	0.479	1.028
	2	0.583	0.604	1.036
	3	0.675	0.700	1.037
	4	0.745	0.773	1.038
	5	0.704	0.729	1.035
	6	0.565	0.582	1.029

Table A.3 (continued)

Archetype	**Story**	**Maximum first-order story drift ratio (%)**	**Maximum second-order story drift ratio (%)**	**Second-to-first-order drift ratio**
Modal	1	0.436	0.447	1.026
	2	0.582	0.602	1.035
	3	0.667	0.691	1.037
	4	0.738	0.766	1.039
	5	0.706	0.731	1.034
	6	0.597	0.615	1.029
Permutation	1	0.440	0.452	1.026
	2	0.582	0.603	1.035
	3	0.661	0.685	1.037
	4	0.735	0.763	1.039
	5	0.742	0.768	1.035
	6	0.605	0.622	1.029
6C-30-Dmax				
Amplified	1	0.656	0.668	1.017
	2	0.882	0.899	1.020
	3	0.994	1.013	1.019
	4	1.065	1.084	1.019
	5	1.054	1.072	1.017
	6	0.856	0.867	1.014
Basic	1	0.670	0.682	1.018
	2	0.918	0.938	1.021
	3	1.023	1.043	1.020
	4	1.062	1.082	1.019
	5	1.052	1.070	1.017
	6	0.854	0.866	1.014
Modal	1	0.659	0.670	1.017
	2	0.882	0.899	1.020
	3	1.024	1.045	1.020
	4	1.072	1.093	1.019
	5	1.044	1.062	1.017
	6	0.896	0.908	1.014
Permutation	1	0.658	0.669	1.017
	2	0.886	0.904	1.020
	3	1.023	1.044	1.020
	4	1.077	1.098	1.019
	5	1.080	1.099	1.018
	6	0.919	0.932	1.014
6C-30-Dmin				
Amplified	1	0.422	0.434	1.027
	2	0.586	0.606	1.034
	3	0.712	0.737	1.036
	4	0.724	0.749	1.035
	5	0.695	0.717	1.032
	6	0.536	0.552	1.030
Basic	1	0.421	0.432	1.028

Table A.3 (continued)

Archetype	**Story**	**Maximum first-order story drift ratio (%)**	**Maximum second-order story drift ratio (%)**	**Second-to-first-order drift ratio**
	2	0.598	0.619	1.035
	3	0.711	0.737	1.036
	4	0.724	0.749	1.035
	5	0.694	0.717	1.032
	6	0.536	0.552	1.030
Modal	1	0.426	0.438	1.028
	2	0.590	0.609	1.033
	3	0.685	0.709	1.035
	4	0.692	0.716	1.035
	5	0.647	0.668	1.032
	6	0.557	0.571	1.025
Permutation	1	0.421	0.432	1.026
	2	0.585	0.604	1.033
	3	0.683	0.708	1.036
	4	0.682	0.706	1.035
	5	0.620	0.637	1.027
	6	0.589	0.604	1.024
6X-20-Dmax				
Amplified	1	0.473	0.477	1.009
	2	1.136	1.166	1.026
	3	1.039	1.061	1.021
	4	1.416	1.450	1.024
	5	1.415	1.446	1.022
	6	1.243	1.269	1.020
Basic	1	0.468	0.473	1.009
	2	1.115	1.144	1.026
	3	1.107	1.131	1.022
	4	1.421	1.456	1.024
	5	1.441	1.474	1.022
	6	1.262	1.289	1.021
Modal	1	0.477	0.481	1.009
	2	1.142	1.174	1.028
	3	1.102	1.126	1.022
	4	1.440	1.476	1.025
	5	1.418	1.450	1.023
	6	1.272	1.298	1.021
Permutation	1	0.461	0.465	1.008
	2	1.182	1.214	1.028
	3	1.069	1.093	1.022
	4	1.468	1.504	1.025
	5	1.465	1.501	1.024
	6	1.349	1.376	1.021
6X-20-Dmin				
Amplified	1	0.388	0.395	1.019
	2	0.742	0.774	1.044

Table A.3 (continued)

Archetype	Story	Maximum first-order story drift ratio (%)	Maximum second-order story drift ratio (%)	Second-to-first-order drift ratio
	3	0.698	0.723	1.035
	4	0.873	0.909	1.041
	5	0.814	0.843	1.036
	6	0.685	0.709	1.035
Basic	1	0.415	0.424	1.021
	2	0.741	0.773	1.043
	3	0.704	0.729	1.035
	4	0.865	0.901	1.041
	5	0.816	0.845	1.036
	6	0.682	0.706	1.035
Modal	1	0.392	0.399	1.020
	2	0.722	0.754	1.044
	3	0.692	0.717	1.036
	4	0.875	0.911	1.041
	5	0.788	0.817	1.036
	6	0.709	0.734	1.035
Permutation	1	0.401	0.408	1.019
	2	0.725	0.758	1.044
	3	0.692	0.717	1.036
	4	0.879	0.915	1.041
	5	0.788	0.816	1.037
	6	0.711	0.736	1.035
6X-30-Dmax				
Amplified	1	0.486	0.491	1.010
	2	0.891	0.911	1.022
	3	0.955	0.972	1.018
	4	1.065	1.084	1.018
	5	1.139	1.159	1.017
	6	0.902	0.914	1.013
Basic	1	0.484	0.488	1.009
	2	0.938	0.960	1.024
	3	0.965	0.983	1.018
	4	1.100	1.121	1.019
	5	1.170	1.191	1.018
	6	0.917	0.929	1.014
Modal	1	0.477	0.481	1.008
	2	0.903	0.925	1.024
	3	0.929	0.946	1.018
	4	1.088	1.108	1.018
	5	1.150	1.170	1.018
	6	0.952	0.964	1.013
Permutation	1	0.462	0.466	1.008
	2	0.915	0.936	1.023
	3	0.930	0.947	1.018
	4	1.085	1.105	1.018

Table A.3 (continued)

Archetype	**Story**	**Maximum first-order story drift ratio (%)**	**Maximum second-order story drift ratio (%)**	**Second-to-first-order drift ratio**
	5	1.179	1.201	1.019
	6	0.944	0.956	1.013
6X-30-Dmin				
Amplified	1	0.367	0.375	1.021
	2	0.576	0.597	1.037
	3	0.707	0.728	1.030
	4	0.664	0.686	1.033
	5	0.727	0.748	1.029
	6	0.519	0.533	1.029
Basic	1	0.369	0.376	1.020
	2	0.638	0.665	1.042
	3	0.686	0.706	1.030
	4	0.704	0.728	1.035
	5	0.711	0.732	1.030
	6	0.529	0.542	1.025
Modal	1	0.363	0.370	1.019
	2	0.612	0.638	1.043
	3	0.653	0.673	1.030
	4	0.717	0.742	1.035
	5	0.677	0.697	1.030
	6	0.574	0.588	1.025
Permutation	1	0.349	0.355	1.018
	2	0.565	0.587	1.039
	3	0.659	0.680	1.032
	4	0.712	0.736	1.033
	5	0.662	0.682	1.030
	6	0.594	0.608	1.024
6Xo-20-Dmax				
Amplified	1	0.559	0.565	1.011
	2	1.136	1.166	1.027
	3	1.090	1.114	1.022
	4	1.393	1.427	1.025
	5	1.440	1.472	1.022
	6	1.284	1.311	1.021
Basic	1	0.588	0.595	1.012
	2	1.109	1.139	1.026
	3	1.130	1.155	1.022
	4	1.417	1.452	1.025
	5	1.477	1.510	1.022
	6	1.313	1.341	1.021
Modal	1	0.575	0.581	1.011
	2	1.129	1.159	1.027
	3	1.152	1.178	1.023
	4	1.415	1.451	1.025
	5	1.503	1.538	1.023

Table A.3 (continued)

Archetype	**Story**	**Maximum first-order story drift ratio (%)**	**Maximum second-order story drift ratio (%)**	**Second-to-first-order drift ratio**
	6	1.337	1.366	1.022
Permutation	1	0.573	0.579	1.011
	2	1.134	1.164	1.027
	3	1.148	1.174	1.023
	4	1.413	1.448	1.025
	5	1.502	1.537	1.023
	6	1.338	1.366	1.022
6Xo-20-Dmax-Tall				
Amplified	1	0.614	0.623	1.014
	2	1.109	1.139	1.027
	3	0.992	1.014	1.022
	4	1.341	1.374	1.025
	5	1.306	1.335	1.022
	6	1.200	1.225	1.021
Basic	1	0.611	0.619	1.014
	2	1.113	1.143	1.027
	3	0.996	1.018	1.022
	4	1.380	1.416	1.025
	5	1.300	1.330	1.023
	6	1.229	1.255	1.021
Modal	1	0.617	0.625	1.014
	2	1.104	1.133	1.026
	3	1.007	1.030	1.022
	4	1.362	1.397	1.025
	5	1.318	1.348	1.023
	6	1.245	1.271	1.021
Permutation	1	0.617	0.625	1.014
	2	1.131	1.162	1.027
	3	1.052	1.077	1.024
	4	1.396	1.432	1.026
	5	1.340	1.373	1.025
	6	1.280	1.308	1.022
6Xo-20-Dmin				
Amplified	1	0.524	0.538	1.026
	2	0.782	0.821	1.050
	3	0.774	0.804	1.040
	4	0.835	0.871	1.044
	5	0.970	1.008	1.039
	6	0.736	0.764	1.039
Basic	1	0.520	0.535	1.028
	2	0.774	0.813	1.050
	3	0.821	0.854	1.040
	4	0.848	0.888	1.047
	5	1.013	1.053	1.040
	6	0.779	0.809	1.040

Table A.3 (continued)

Archetype	**Story**	**Maximum first-order story drift ratio (%)**	**Maximum second-order story drift ratio (%)**	**Second-to-first-order drift ratio**
Modal	1	0.528	0.542	1.028
	2	0.765	0.803	1.051
	3	0.819	0.852	1.041
	4	0.855	0.894	1.046
	5	0.991	1.031	1.040
	6	0.756	0.787	1.040
Permutation	1	0.472	0.484	1.026
	2	0.746	0.783	1.051
	3	0.826	0.859	1.040
	4	0.841	0.880	1.045
	5	1.001	1.041	1.040
	6	0.768	0.799	1.039
6Xo-30-Dmax				
Amplified	1	0.643	0.651	1.014
	2	1.020	1.044	1.024
	3	0.991	1.008	1.018
	4	1.211	1.237	1.021
	5	1.282	1.306	1.019
	6	1.062	1.079	1.016
Basic	1	0.642	0.651	1.014
	2	1.050	1.076	1.025
	3	0.983	1.001	1.018
	4	1.210	1.236	1.021
	5	1.283	1.307	1.019
	6	1.059	1.076	1.016
Modal	1	0.648	0.657	1.013
	2	1.029	1.054	1.025
	3	0.967	0.985	1.018
	4	1.212	1.238	1.021
	5	1.274	1.298	1.019
	6	1.118	1.136	1.016
Permutation	1	0.654	0.663	1.013
	2	0.994	1.017	1.024
	3	0.976	0.993	1.018
	4	1.184	1.209	1.021
	5	1.268	1.292	1.019
	6	1.123	1.141	1.016
6Xo-30-Dmax-Tall				
Amplified	1	0.601	0.609	1.013
	2	1.048	1.076	1.027
	3	1.024	1.044	1.020
	4	1.202	1.230	1.023
	5	1.300	1.327	1.020
	6	1.041	1.056	1.015
Basic	1	0.599	0.607	1.013

Table A.3 (continued)

Archetype	Story	Maximum first-order story drift ratio (%)	Maximum second-order story drift ratio (%)	Second-to-first-order drift ratio
	2	1.046	1.074	1.027
	3	1.039	1.060	1.020
	4	1.217	1.246	1.024
	5	1.297	1.323	1.020
	6	1.035	1.054	1.018
Modal	1	0.607	0.615	1.013
	2	1.030	1.057	1.026
	3	1.027	1.047	1.020
	4	1.212	1.239	1.023
	5	1.273	1.300	1.021
	6	1.115	1.134	1.017
Permutation	1	0.615	0.623	1.014
	2	0.996	1.021	1.025
	3	1.033	1.054	1.020
	4	1.211	1.238	1.023
	5	1.272	1.299	1.021
	6	1.124	1.143	1.017
6Xo-30-Dmin				
Amplified	1	0.549	0.563	1.026
	2	0.805	0.845	1.050
	3	0.775	0.805	1.038
	4	0.844	0.878	1.041
	5	0.858	0.887	1.034
	6	0.596	0.616	1.034
Basic	1	0.538	0.552	1.027
	2	0.793	0.833	1.050
	3	0.820	0.852	1.038
	4	0.817	0.851	1.041
	5	0.901	0.932	1.035
	6	0.633	0.655	1.034
Modal	1	0.551	0.566	1.027
	2	0.772	0.812	1.051
	3	0.810	0.841	1.038
	4	0.815	0.849	1.042
	5	0.881	0.913	1.036
	6	0.599	0.618	1.032
Permutation	1	0.527	0.541	1.026
	2	0.760	0.799	1.051
	3	0.800	0.831	1.038
	4	0.820	0.854	1.042
	5	0.875	0.907	1.036
	6	0.604	0.620	1.027
9X-30-Dmax				
Amplified	1	0.492	0.498	1.012
	2	0.918	0.952	1.036

Table A.3 (continued)

Archetype	Story	Maximum first-order story drift ratio (%)	Maximum second-order story drift ratio (%)	Second-to-first-order drift ratio
	3	0.995	1.022	1.027
	4	1.273	1.318	1.035
	5	1.335	1.377	1.031
	6	1.487	1.536	1.033
	7	1.575	1.624	1.031
	8	1.519	1.566	1.031
	9	1.553	1.598	1.029
Basic	1	0.490	0.495	1.011
	2	0.952	0.988	1.038
	3	1.002	1.029	1.027
	4	1.304	1.352	1.037
	5	1.370	1.414	1.032
	6	1.517	1.568	1.033
	7	1.627	1.679	1.032
	8	1.590	1.641	1.032
	9	1.595	1.643	1.030
Modal	1	0.464	0.468	1.009
	2	0.888	0.922	1.038
	3	0.979	1.006	1.027
	4	1.364	1.413	1.036
	5	1.224	1.260	1.029
	6	1.569	1.622	1.034
	7	1.574	1.626	1.033
	8	1.645	1.694	1.030
	9	1.546	1.593	1.030
Permutation	1	0.450	0.454	1.010
	2	0.918	0.951	1.036
	3	0.989	1.016	1.028
	4	1.370	1.420	1.037
	5	1.325	1.369	1.033
	6	1.600	1.654	1.034
	7	1.604	1.661	1.035
	8	1.677	1.729	1.031
	9	1.597	1.647	1.031
9Xo-30-Dmax				
Amplified	1	0.652	0.663	1.018
	2	1.102	1.144	1.039
	3	1.072	1.104	1.030
	4	1.454	1.511	1.039
	5	1.409	1.456	1.033
	6	1.610	1.669	1.037
	7	1.694	1.751	1.034
	8	1.729	1.791	1.036
	9	1.684	1.737	1.031
Basic	1	0.640	0.650	1.016
	2	1.166	1.214	1.041

Table A.3 (continued)

Archetype	Story	Maximum first-order story drift ratio (%)	Maximum second-order story drift ratio (%)	Second-to-first-order drift ratio
	3	1.095	1.129	1.031
	4	1.496	1.555	1.040
	5	1.416	1.463	1.034
	6	1.670	1.732	1.037
	7	1.700	1.759	1.035
	8	1.747	1.809	1.036
	9	1.704	1.759	1.032
Modal	1	0.651	0.662	1.017
	2	1.146	1.192	1.040
	3	1.083	1.115	1.030
	4	1.486	1.546	1.040
	5	1.406	1.454	1.034
	6	1.673	1.735	1.037
	7	1.701	1.761	1.035
	8	1.735	1.795	1.035
	9	1.642	1.695	1.032
Permutation	1	0.653	0.664	1.016
	2	1.073	1.114	1.038
	3	1.105	1.139	1.031
	4	1.398	1.451	1.038
	5	1.416	1.463	1.033
	6	1.617	1.676	1.037
	7	1.711	1.771	1.035
	8	1.677	1.734	1.034
	9	1.631	1.683	1.032

Table A.4: Archetype periods

Archetype	Fundamental period (FEMA P695) (s)	Fundamental period (s)	2nd mode period (s)	3rd mode period (s)	4th mode period (s)
2C-20-Dmax					
Amplified	0.322	0.340	0.162	n/a	n/a
Basic	0.322	0.340	0.164	n/a	n/a
Modal	0.322	0.340	0.159	n/a	n/a
Permutation	0.322	0.340	0.159	n/a	n/a
2C-20-Dmin					
Amplified	0.345	0.415	0.185	n/a	n/a
Basic	0.345	0.419	0.187	n/a	n/a
Modal	0.345	0.415	0.182	n/a	n/a
Permutation	0.345	0.419	0.184	n/a	n/a
2C-30-Dmax					
Amplified	0.322	0.350	0.168	n/a	n/a
Basic	0.322	0.357	0.174	n/a	n/a
Modal	0.322	0.357	0.170	n/a	n/a
Permutation	0.322	0.357	0.170	n/a	n/a
2C-30-Dmin					
Amplified	0.345	0.436	0.191	n/a	n/a
Basic	0.345	0.437	0.194	n/a	n/a
Modal	0.345	0.436	0.186	n/a	n/a
Permutation	0.345	0.436	0.186	n/a	n/a
2X-20-Dmax					
Amplified	0.322	0.339	0.164	n/a	n/a
Basic	0.322	0.339	0.164	n/a	n/a
Modal	0.322	0.339	0.164	n/a	n/a
Permutation	0.322	0.339	0.164	n/a	n/a
2X-20-Dmin					
Amplified	0.345	0.418	0.182	n/a	n/a
Basic	0.345	0.418	0.182	n/a	n/a
Modal	0.345	0.421	0.182	n/a	n/a
Permutation	0.345	0.421	0.182	n/a	n/a
2X-30-Dmax					
Amplified	0.322	0.338	0.200	n/a	n/a
Basic	0.322	0.356	0.200	n/a	n/a
Modal	0.322	0.356	0.200	n/a	n/a
Permutation	0.322	0.356	0.200	n/a	n/a
2X-30-Dmin					
Amplified	0.345	0.429	0.201	n/a	n/a
Basic	0.345	0.429	0.201	n/a	n/a
Modal	0.345	0.429	0.201	n/a	n/a
Permutation	0.345	0.429	0.201	n/a	n/a
2Xo-20-Dmax					
Amplified	0.322	0.383	0.187	n/a	n/a
Basic	0.322	0.384	0.188	n/a	n/a
Modal	0.322	0.383	0.187	n/a	n/a
Permutation	0.322	0.383	0.187	n/a	n/a

Table A.4 (continued)

Archetype	**Fundamental period (FEMA P695) (s)**	**Fundamental period (s)**	**2^{nd} mode period (s)**	**3^{rd} mode period (s)**	**4^{th} mode period (s)**
2Xo-20-Dmin					
Amplified	0.345	0.491	0.221	n/a	n/a
Basic	0.345	0.494	0.229	n/a	n/a
Modal	0.345	0.491	0.221	n/a	n/a
Permutation	0.345	0.494	0.229	n/a	n/a
2Xo-30-Dmax					
Amplified	0.322	0.408	0.196	n/a	n/a
Basic	0.322	0.408	0.196	n/a	n/a
Modal	0.322	0.408	0.196	n/a	n/a
Permutation	0.322	0.408	0.196	n/a	n/a
2Xo-30-Dmax-Heavy					
Amplified	0.322	0.399	0.214	n/a	n/a
Basic	0.322	0.399	0.214	n/a	n/a
Modal	0.322	0.399	0.214	n/a	n/a
Permutation	0.322	0.399	0.214	n/a	n/a
2Xo-30-Dmin					
Amplified	0.345	0.516	0.219	n/a	n/a
Basic	0.345	0.518	0.222	n/a	n/a
Modal	0.345	0.518	0.222	n/a	n/a
Permutation	0.345	0.518	0.222	n/a	n/a
3C-20-Dmax					
Amplified	0.437	0.460	0.198	0.136	n/a
Basic	0.437	0.463	0.198	0.138	n/a
Modal	0.437	0.463	0.195	0.136	n/a
Permutation	0.437	0.463	0.194	0.136	n/a
3C-20-Dmin					
Amplified	0.468	0.571	0.234	0.156	n/a
Basic	0.468	0.578	0.236	0.160	n/a
Modal	0.468	0.577	0.227	0.158	n/a
Permutation	0.468	0.577	0.225	0.157	n/a
3C-30-Dmax					
Amplified	0.437	0.468	0.205	0.143	n/a
Basic	0.437	0.468	0.205	0.143	n/a
Modal	0.437	0.463	0.202	0.142	n/a
Permutation	0.437	0.463	0.201	0.141	n/a
3C-30-Dmin					
Amplified	0.468	0.589	0.233	0.168	n/a
Basic	0.468	0.595	0.238	0.170	n/a
Modal	0.468	0.589	0.229	0.167	n/a
Permutation	0.468	0.575	0.222	0.163	n/a
3X-20-Dmax					
Amplified	0.437	0.459	0.195	0.139	n/a
Basic	0.437	0.463	0.198	0.141	n/a
Modal	0.437	0.463	0.195	0.139	n/a
Permutation	0.437	0.462	0.193	0.138	n/a

Table A.4 (continued)

Archetype	Fundamental period (FEMA P695) (s)	Fundamental period (s)	2nd mode period (s)	3rd mode period (s)	4th mode period (s)
3X-20-Dmin					
Amplified	0.468	0.589	0.230	0.164	n/a
Basic	0.468	0.587	0.230	0.164	n/a
Modal	0.468	0.589	0.229	0.164	n/a
Permutation	0.468	0.588	0.226	0.162	n/a
3X-30-Dmax					
Amplified	0.437	0.444	0.206	0.152	n/a
Basic	0.437	0.452	0.207	0.158	n/a
Modal	0.437	0.452	0.206	0.156	n/a
Permutation	0.437	0.452	0.204	0.155	n/a
3X-30-Dmin					
Amplified	0.468	0.569	0.229	0.176	n/a
Basic	0.468	0.571	0.233	0.177	n/a
Modal	0.468	0.571	0.229	0.174	n/a
Permutation	0.468	0.571	0.229	0.173	n/a
3Xo-20-Dmax					
Amplified	0.437	0.500	0.220	0.153	n/a
Basic	0.437	0.502	0.221	0.154	n/a
Modal	0.437	0.499	0.219	0.151	n/a
Permutation	0.437	0.499	0.219	0.151	n/a
3Xo-20-Dmax-Tall					
Amplified	0.478	0.536	0.235	0.156	n/a
Basic	0.478	0.541	0.237	0.157	n/a
Modal	0.478	0.541	0.236	0.157	n/a
Permutation	0.478	0.541	0.235	0.156	n/a
3Xo-20-Dmin					
Amplified	0.468	0.637	0.276	0.183	n/a
Basic	0.468	0.640	0.277	0.184	n/a
Modal	0.468	0.640	0.276	0.184	n/a
Permutation	0.468	0.640	0.276	0.184	n/a
3Xo-30-Dmax					
Amplified	0.437	0.497	0.219	0.159	n/a
Basic	0.437	0.499	0.221	0.162	n/a
Modal	0.437	0.499	0.217	0.161	n/a
Permutation	0.437	0.499	0.217	0.161	n/a
3Xo-30-Dmax-Tall					
Amplified	0.478	0.530	0.234	0.166	n/a
Basic	0.478	0.533	0.235	0.166	n/a
Modal	0.478	0.534	0.236	0.166	n/a
Permutation	0.478	0.534	0.236	0.166	n/a
3Xo-30-Dmin					
Amplified	0.468	0.665	0.271	0.192	n/a
Basic	0.468	0.667	0.276	0.194	n/a
Modal	0.468	0.667	0.273	0.193	n/a
Permutation	0.468	0.667	0.273	0.193	n/a

Table A.4 (continued)

Archetype	Fundamental period (FEMA P695) (s)	Fundamental period (s)	2^{nd} mode period (s)	3^{rd} mode period (s)	4^{th} mode period (s)
4C-20-Dmax					
Amplified	0.542	0.587	0.234	0.155	0.120
Basic	0.542	0.586	0.236	0.157	0.120
Modal	0.542	0.589	0.233	0.155	0.119
Permutation	0.542	0.589	0.233	0.155	0.119
4C-20-Dmin					
Amplified	0.581	0.769	0.302	0.197	0.145
Basic	0.581	0.776	0.304	0.197	0.145
Modal	0.581	0.773	0.297	0.194	0.143
Permutation	0.581	0.769	0.295	0.193	0.142
4C-30-Dmax					
Amplified	0.542	0.587	0.244	0.163	0.131
Basic	0.542	0.588	0.246	0.166	0.131
Modal	0.542	0.583	0.241	0.163	0.128
Permutation	0.542	0.586	0.240	0.162	0.131
4C-30-Dmin					
Amplified	0.581	0.758	0.289	0.190	0.153
Basic	0.581	0.760	0.291	0.192	0.155
Modal	0.581	0.760	0.283	0.187	0.152
Permutation	0.581	0.760	0.283	0.187	0.152
4X-20-Dmax					
Amplified	0.542	0.584	0.218	0.154	0.120
Basic	0.542	0.587	0.218	0.155	0.122
Modal	0.542	0.589	0.215	0.156	0.122
Permutation	0.542	0.589	0.215	0.156	0.122
4X-20-Dmin					
Amplified	0.581	0.771	0.277	0.182	0.145
Basic	0.581	0.783	0.280	0.184	0.148
Modal	0.581	0.787	0.273	0.183	0.147
Permutation	0.581	0.765	0.268	0.182	0.146
4X-30-Dmax					
Amplified	0.542	0.553	0.224	0.200	0.173
Basic	0.542	0.556	0.227	0.200	0.175
Modal	0.542	0.551	0.218	0.200	0.173
Permutation	0.542	0.544	0.217	0.200	0.171
4X-30-Dmin					
Amplified	0.581	0.763	0.275	0.201	0.195
Basic	0.581	0.763	0.275	0.201	0.195
Modal	0.581	0.771	0.267	0.201	0.196
Permutation	0.581	0.771	0.267	0.201	0.196
4Xo-20-Dmax					
Amplified	0.542	0.604	0.245	0.167	0.125
Basic	0.542	0.610	0.248	0.169	0.125
Modal	0.542	0.614	0.244	0.169	0.126
Permutation	0.542	0.614	0.244	0.169	0.126

Table A.4 (continued)

Archetype	**Fundamental period (FEMA P695) (s)**	**Fundamental period (s)**	**2^{nd} mode period (s)**	**3^{rd} mode period (s)**	**4^{th} mode period (s)**
4Xo-20-Dmin					
Amplified	0.581	0.845	0.330	0.216	0.162
Basic	0.581	0.845	0.330	0.216	0.162
Modal	0.581	0.847	0.326	0.218	0.163
Permutation	0.581	0.847	0.326	0.218	0.163
4Xo-30-Dmax					
Amplified	0.542	0.611	0.250	0.176	0.143
Basic	0.542	0.612	0.252	0.177	0.143
Modal	0.542	0.613	0.248	0.178	0.143
Permutation	0.542	0.613	0.248	0.178	0.143
4Xo-30-Dmax-Heavy					
Amplified	0.542	0.626	0.268	0.200	0.160
Basic	0.542	0.634	0.269	0.203	0.165
Modal	0.542	0.627	0.264	0.202	0.158
Permutation	0.542	0.625	0.266	0.203	0.161
4Xo-30-Dmin					
Amplified	0.581	0.862	0.325	0.213	0.172
Basic	0.581	0.866	0.328	0.217	0.174
Modal	0.581	0.857	0.316	0.212	0.172
Permutation	0.581	0.857	0.316	0.212	0.172
6C-20-Dmax					
Amplified	0.735	0.896	0.325	0.197	0.152
Basic	0.735	0.906	0.328	0.197	0.152
Modal	0.735	0.918	0.327	0.197	0.154
Permutation	0.735	0.919	0.326	0.195	0.152
6C-20-Dmin					
Amplified	0.787	1.215	0.435	0.254	0.195
Basic	0.787	1.224	0.435	0.254	0.195
Modal	0.787	1.219	0.429	0.251	0.195
Permutation	0.787	1.223	0.434	0.251	0.199
6C-30-Dmax					
Amplified	0.735	0.859	0.332	0.204	0.162
Basic	0.735	0.868	0.334	0.206	0.164
Modal	0.735	0.862	0.329	0.203	0.162
Permutation	0.735	0.865	0.330	0.202	0.162
6C-30-Dmin					
Amplified	0.787	1.181	0.437	0.264	0.204
Basic	0.787	1.187	0.441	0.265	0.205
Modal	0.787	1.179	0.432	0.263	0.202
Permutation	0.787	1.175	0.425	0.259	0.201
6X-20-Dmax					
Amplified	0.735	0.914	0.310	0.183	0.147
Basic	0.735	0.923	0.309	0.185	0.147
Modal	0.735	0.929	0.310	0.183	0.148
Permutation	0.735	0.929	0.311	0.180	0.148

Table A.4 (continued)

Archetype	**Fundamental period (FEMA P695) (s)**	**Fundamental period (s)**	**2^{nd} mode period (s)**	**3^{rd} mode period (s)**	**4^{th} mode period (s)**
6X-20-Dmin					
Amplified	0.787	1.250	0.416	0.239	0.187
Basic	0.787	1.256	0.421	0.241	0.188
Modal	0.787	1.253	0.415	0.238	0.188
Permutation	0.787	1.253	0.413	0.237	0.187
6X-30-Dmax					
Amplified	0.735	0.822	0.303	0.201	0.190
Basic	0.735	0.834	0.310	0.201	0.195
Modal	0.735	0.831	0.306	0.201	0.192
Permutation	0.735	0.829	0.304	0.201	0.187
6X-30-Dmin					
Amplified	0.787	1.140	0.407	0.241	0.202
Basic	0.787	1.159	0.412	0.243	0.202
Modal	0.787	1.156	0.405	0.235	0.202
Permutation	0.787	1.145	0.396	0.232	0.202
6Xo-20-Dmax					
Amplified	0.735	0.933	0.335	0.209	0.160
Basic	0.735	0.939	0.336	0.209	0.161
Modal	0.735	0.945	0.335	0.207	0.163
Permutation	0.735	0.945	0.336	0.207	0.163
6Xo-20-Dmax-Tall					
Amplified	0.770	0.967	0.359	0.217	0.168
Basic	0.770	0.972	0.361	0.218	0.169
Modal	0.770	0.971	0.361	0.216	0.171
Permutation	0.770	0.980	0.361	0.217	0.172
6Xo-20-Dmin					
Amplified	0.787	1.322	0.478	0.277	0.213
Basic	0.787	1.339	0.481	0.279	0.214
Modal	0.787	1.338	0.478	0.277	0.214
Permutation	0.787	1.320	0.472	0.272	0.211
6Xo-30-Dmax					
Amplified	0.735	0.877	0.338	0.217	0.169
Basic	0.735	0.881	0.340	0.218	0.170
Modal	0.735	0.879	0.340	0.215	0.170
Permutation	0.735	0.874	0.337	0.213	0.170
6Xo-30-Dmax-Tall					
Amplified	0.770	0.932	0.357	0.223	0.176
Basic	0.770	0.936	0.358	0.226	0.177
Modal	0.770	0.935	0.359	0.222	0.179
Permutation	0.770	0.932	0.357	0.221	0.178
6Xo-30-Dmin					
Amplified	0.787	1.282	0.466	0.275	0.211
Basic	0.787	1.292	0.469	0.277	0.214
Modal	0.787	1.294	0.468	0.273	0.218
Permutation	0.787	1.290	0.465	0.271	0.217

Table A.4 (continued)

Archetype	**Fundamental period (FEMA P695) (s)**	**Fundamental period (s)**	**2$^{\text{nd}}$ mode period (s)**	**3$^{\text{rd}}$ mode period (s)**	**4$^{\text{th}}$ mode period (s)**
9X-30-Dmax					
Amplified	0.996	1.313	0.446	0.268	0.203
Basic	0.996	1.328	0.452	0.269	0.204
Modal	0.996	1.315	0.445	0.261	0.203
Permutation	0.996	1.334	0.445	0.262	0.203
9Xo-30-Dmax					
Amplified	0.996	1.387	0.489	0.291	0.220
Basic	0.996	1.402	0.493	0.292	0.221
Modal	0.996	1.398	0.489	0.286	0.217
Permutation	0.996	1.385	0.487	0.286	0.217

Vita

Peter Talley is a native of Knoxville, TN, where he graduated as valedictorian from Austin-East Magnet High School. He then attended Tennessee Tech University, beginning in mechanical engineering and switching to civil when thermodynamics didn't agree with him. He graduated in December 2015 with a Bachelor of Science in Civil Engineering from TTU and began his Master of Science in Civil Engineering program at the University of Tennessee, Knoxville in the fall of 2016. He will be continuing at UTK in the spring of 2019, pursuing a Ph.D. in Civil Engineering under Dr. Mark Denavit.